INTERPRETATION OF THE GRAVITY MAP OF CALIFORNIA AND ITS CONTINENTAL MARGIN

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By

H.W. Oliver, Editor

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CALIFORNIA DIVISION OF MINES AND GEOLOGY
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TABLE OF CONTENTS

APPENDIX

FIGURES

TABLES

Layout by Louise Huckaby

UNITS AND ABBREVIATIONS USED IN THIS REPORT

Units

cm/s^2	–	centimeters per second per second
mgal	–	milligals = $10^{-3}cm/s^2$
km	–	kilometer
m	–	meter
mm	–	millimeters
m.y.	–	million years
g/cm^3	–	grams per cubic centimeter (used for density contrast $\Delta\rho$)

Abbreviations

USGS	–	U.S. Geological Survey
CDMG	–	California Division of Mines and Geology
NOAA	–	U.S. National Oceanic and Atmospheric Administration
DMA/TC	–	U.S. Defense Mapping Agency, Topographic Command, Washington, D.C.
DMA/AC	–	U.S. Defense Mapping Agency, Aerospace Center, St. Louis, Mo.
U.C.	–	University of California
N.	–	north
W.	–	west
$\Delta\rho$	–	density contrast (delta rho)

ABSTRACT

A gravity map of California has been compiled and overprinted on the Fault map of California, scale 1:750,000. The gravity overlay consists of Bouguer anomaly contours onshore and free–air anomaly contours offshore at intervals of 5 mgal and 10 mgal, respectively. The compilation is based on over 50,000 gravity measurements on land and 30,000 measurements at sea. Both land and sea measurements were made relative to the Woollard and Rose (1963) gravity datum and reduced using the International Gravity formula of 1930. The land data were further reduced using a Bouguer reduction density of 2.67 g/cm^3, and include curvature and terrain corrections to a distance of 166.7 km for all 50,000 stations.

Bouguer anomalies range from about –280 mgal in Long Valley on the east side of the Sierra Nevada to about +30 mgal along several sections of the California coastline, although they increase further on the offshore islands to as much as +80 mgal near the center of Santa Cruz Island west of Santa Barbara. Free–air anomalies on the continental margin range from –110 mgal in the Santa Monica Basin to +60 mgal on the south shore of Santa Cruz Island and over San Juan Seamount about 300 km west of San Diego.

A generalized topographic map of California based on averaging elevations to a distance of about 40 km shows a striking correlation with Bouguer anomalies. The ratio at low elevations is about –1 mgal/10 m increase in average elevation, but at average elevations over 2 km this decreases to about –0.8 mgal/10 m. Local departures of Bouguer anomalies from those predicted by average elevations range up to ±50 mgal and are discussed by provinces from southwest to northeast.

In offshore southern California, regional Bouguer gravity decreases toward the northeast due to a northeastward thickening of the crust. Less positive free–air gravity anomalies usually occur over basins and more positive free–air anomalies usually occur over submarine ridges, knolls, and banks because these anomalies are uncorrected for topography. Bouguer anomalies and topography show a similar though less strong correlation because sequences of relatively young lower density rocks usually underlie basins whereas relatively old, higher density rocks usually underlie submarine ridges, knolls, and banks. Bouguer gradients and anomaly trends conform to the general northwest–southeast structural grain and in some places express the offshore extensions of major faults.

The San Gabriel Mountains are characterized by a general northeast decrease in Bouguer anomalies from –60 to –90 mgal matching a northeast increase in average elevation from 600 to 900 m. Bouguer anomalies in the San Bernardino Mountains are stronger, about –120 mgal over their northern sector, and this low corresponds to an average elevation of 1200 m, indicating that the ranges are in regional isostatic balance. Northeast of the San Gabriel Mountains, average elevation continues to rise well out into the Mojave Desert in spite of the sharp decrease in local elevation. Bouguer anomalies similarly decrease to a minimum value of about –105 mgal over bedrock in the southwestern part of the Mojave Desert before starting to increase farther north with decreasing average elevation. The location and shape of this regional gravity low corresponds closely with a reported region of aseismic uplift and may be related to it.

In the Peninsular Ranges, Bouguer anomalies measure about –20 mgal along the coast, decrease eastward to a minimum value of –90 mgal at the maximum average elevation of about 1000 m, and increase farther east to –25 mgal at the lower eastern edge of the province, in general accordance with isostasy. However, gravity is abnormally high and benchlike over the western part of the southern California batholith, and the gravity bench extends to the eastern limit of exposed gabbroic plutons within the batholith.A north–striking gravity gradient along this eastern limit serves to divide the batholith into two parts and is not offset where it crosses the Elsinore fault near Lake Henshaw. Another gravity gradient is coincident with the north end of the San Jacinto fault and becomes very steep near San Bernardino, producing a gravity step of 20 mgal down to the northeast. Local gravity highs of about 25 mgal occur over structural highs in the Palos Verdes and San Joaquin Hills; others of 5 to 10 mgal occur over several bodies of gabbro. A major gravity low of –75 mgal occurs over Los Angeles basin.

Bouguer anomaly values are high (average level –35 mgal) over the southern half of the Salton Trough where a sedimentary basin about 5.9 km deep (drill hole and seismic–refraction data) fails to display an associated gravity low that should exceed –50 mgal. The high regional values are probably caused by extensional thinning of the earth's crust beneath the basin to values 8–10 km thinner than adjacent areas and also possibly by density increase of the basement due to

basaltic intrusions. The extension is related to the spreading centers in the Gulf of California and the associated transform faults striking northwest into southern California. A gravity high over the Orocopia Schist on the northeast side of the San Andreas fault may correlate with other gravity highs over the Pelona Schist on the opposite side of the fault 90 and 300 km to the northwest. These three highs may reflect uplifted former oceanic crust at a shallow depth beneath the schists. Other gravity highs up to 20 mgal in amplitude associated with geothermal areas probably reflect density increases due to metamorphism of near-surface sedimentary rocks. In the northern part of the Salton Trough a gravity low defines a valley basin containing a maximum interpreted sediment thickness of at least 4.7 km.

Bouguer anomalies in the Mojave Desert Province range from more than –25 mgal in some of the mountain ranges to less than –145 mgal in Ivanpah Valley. On a regional scale, the gravity field may reflect crustal thickness; seismic–refraction measurements indicate that the thickness of the crust ranges from about 20 km in the Salton Sea Province to the south to 27 km or more in the northern part of the Mojave. The province is characterized by a general random pattern of local anomalies. In general, positive anomalies tend to follow mountain ranges and negative anomalies follow the intervening valleys. The strongest positive anomalies are related to relatively dense Precambrian igneous and metamorphic rocks and Mesozoic mafic rocks. The strongest negative anomalies are related to Cenozoic sedimentary deposits.

Free–air gravity anomalies outline major structural ridges and basins on the central California continental margin, a region of large translational tectonic movements. The Farallon ridge, from Point Arena to Pigeon Point, is underlain in large part by granitic rocks and is truncated on the southeast by the San Gregorio fault, although the associated anomaly continues east of the fault over the Ben Lomond batholith. This extension may rule out large right–slip offset on the fault, but it may also be fortuitous. Gravity anomalies over Santa Lucia bank parallel the northwest–trending bank morphology, but those over Santa Maria basin to the east trend northeast. The anomalies change trend abruptly across the Santa Lucia Bank fault and may indicate structural trends below the basin that are difficult to map by other techniques. Gravity interpretation has not yet provided new insights for the Bodega, outer Santa Cruz, or Point Arena basins. On the margin of subduction, north of Cape Mendocino, a free–air gravity low of –80 mgal occurs at the base of the continental slope just north of the Mendocino fault. Seismic data have not revealed a very thick section of sediment here. The extreme low may represent some effect of the tectonic intersection of the Mendocino fault and Cascadia subduction zone.

Bouguer anomalies in the Coast Ranges Province decrease, and crustal thickness increases in general both north and south of San Francisco. The Bouguer anomalies in this province also decrease inland from the coastline largely because of the transition from thin oceanic to thick continental crust. In the northern part of the Coast Ranges this gradient over the imbricated Franciscan assemblage and melange is relatively smooth; to the south the gradient is interrupted by a complex pattern of local anomalies reflecting more complex geology. The striking contrast between the extreme geological complexity of the southern part of the Coast Ranges and the relatively regular geology of the northern part may be attributable to differences between the length of time since the two parts were subject to eastward subduction. A northward migration of the triple junction now located offshore at latitude 40°20'N terminated eastward subduction in the northern part much more recently than it did eastward subduction in the southern part. Local gravity features in the southern province trend northwest or north, paralleling regional geologic structure. Major positive anomalies to the south of latitude 39°N are caused by granitic, mafic, and Franciscan rocks. Major negative anomalies are related to bodies of Tertiary and Quaternary sedimentary rocks. Unusual anomalies are: (a) a gravity high of 50 mgal over a diabase body (Mt. Diablo, lat 37°55'N) having the shape either of a piercement structure or, more likely, an antiformal sheet, (2) a gravity low of 30 mgal associated with a possible magma chamber (The Geysers, lat 38°55'N), and (3) a gravity low of 20 mgal caused by a graben (east of San Jose, lat 37°20'N) extending into the lower crust or upper mantle.

Connected gravity lows of 20 to 60 mgal occur over thicknesses of 6 to 11 km of Cretaceous and Cenozoic sedimentary rocks along the west side of the Great Valley. The axis of the connected lows determines the average axis of the asymmetrical syncline, which has shifted 20 km to the east since Cretaceous time. Connected gravity highs of 10 to 50 mgal extend from Red Bluff to Fresno near the center of the valley. A sharper group of connected highs of 10 to 30 mgal extends along the southeast side of the valley and into the Sierra Nevada near Porterville, where they are associated with remnants of 300 million–year–old oceanic crust. The similarity of the gravity highs in the central part of the valley suggests that they reflect buried fragments of oceanic crust younger than those exposed in the Sierra Nevada and older than the 151–160 million year old Coast Range ophiolite. Gravity lows of about 40 mgal reveal two salients of the Sierra Nevada batholith that extend westward under the Great Valley near Sacramento and Fresno.

The Sierra Nevada is characterized by an eastward decrease in Bouguer anomalies from a high value of about –50 mgal at the west edge to a gravity low whose axis is located near and generally parallel to the Sierra crest. Bouguer anomalies along the axis range from –130 mgal east of Bakersfield to –240 mgal west of Mammoth. East of the Sierra crest, gravity generally rises 10 to 20 mgal to the east edge of the mountains. The general form and magnitude of the Bouguer anomalies are similar to average elevations, but the incremental ratio between the two (about –80 mgal/km) is smaller in the Sierra Nevada than in other parts of the California because the corresponding compensating mass is deeper (40 to 55 km) and the solid angle subtended at the surface is less. Local gravity highs of 20 to 40 mgal are associated with ophiolites at several localities along the Melones and Bear Mountain faults. Unconnected local lows of as much as –30 mgal over isolated felsic plutons in the northwest Sierra Nevada indicate that the plutons are not connected at depth. A gravity low of a least –15 mgal over Lake Tahoe indicates the presence of at least 800 m of sediment.

Regional gravity in the Great Basin increases east of the Sierra Nevada with decreasing average elevation according to the ratio –1 mgal/10 m. Within the Great Basin positive residuals are associated with Precambrian metamorphic and Tertiary volcanic rocks and negative residuals with Mesozoic granitic rocks. Residual gravity lows of –15 to –50 mgal over nine major basins reflect sedimentary thicknesses of 0.6 to 3.0 km. The average density contrast between sediments in the basins and surrounding bedrock ranges from 0.35 g/cm^3 for Indian Wells Valley to 0.95 g/cm^3 for Honey Lake Valley. Steep gravity gradients reveal the locations of many buried normal faults and indicate that some fault zones consist of a series of step faults combined with warping.

Gravity highs in the Klamath Mountains are generally associated with sheets of ultramafic rocks that are probably parts of ophiolite complexes. On the east side of the province the major gravity highs extend north–south along the Trinity ophiolite assemblage, but locally ophiolite is not indicated where extensive serpentinization has reduced the density of the ultramafic rocks. From gravity and aeromagnetic data the interpreted extent of the ophiolite is over 170 km in a north–south direction, but it may consist of three different ophiolite masses now tectonically juxtaposed along northeast–striking faults.

In the Cascade Range, subcircular gravity minima 50 to 70 km in diameter are associated with the major volcanoes Lassen and Shasta and probably show the combined effects of low–density volcanic rocks and concealed batholiths. The form and location of the oblong Lassen anomaly, which is centered on the gap between the Klamath Mountains and the Sierra Nevada, offer support for the proposed rift separating these provinces. The northeast–sloping regional gravity gradient in this area is related to the topography, which probably postdates the rifting. Gravity trends in the Modoc Plateau east of the Cascade Range strike north and northwest, representing faults or steep downwarps associated with structural trends paralleling those in the Basin and Range Province. A line of closed gravity highs trends northeast across the plateau and may represent a basement ridge below the volcanic rocks, having an elevation of about 2.4 km if the density contrast is 0.2 g/cm^3.

GENERAL INTRODUCTION

by H. W. Oliver[1]

The gravity map of California is the result of a combined 10–year effort by the California Division of Mines and Geology (CDMG), the U.S. Geology Survey (USGS), several campuses of the University of California (U.C.), and the University of Oregon. The U.S. Defense Mapping Agency provided help in instrumentation and financial assistance without which the map in its present form would not have been possible. Figure 1 shows the various areas of responsibility, and Figure 2 shows the publication status, as of 1979, of the 1:250,000–scale gravity maps in California and the data on which they are based. Table 1 keys the report numbers in Figure 2 to corresponding references.

Figure 1. Index map of California and its continental margin showing areas for which various State and Federal agencies and universities were responsible for obtaining and compiling gravity data.

As indicated on the map itself, this 1:750,000–scale compilation is primarily a reduction to one–third of the published size and mosaic of the 1:250,000 maps, but it also includes data for the seven unpublished sheets in southern California and for unpublished sheets in offshore California between latitudes 35°N and 40°N. It also incorporates considerable ocean–bottom data along the inner shelf between latitudes 35°N and 42°N made available by the National Oceanic and Atmospheric Administration (NOAA) (A. Bilik, written communication, 1973), and, in the area between latitudes 36°N and 37°N, from theses done at the U.S. Naval Postgraduate School in Monterey, California (Brooks, 1973; Cronyn, 1973; Souto, 1973; Spikes, 1973; and Woodson, 1973). These data were particularly helpful in resolving problems in continuity between the free–air anomalies obtained with surface ships along the outer shelf and the Bouguer anomalies on land. Some of these problems are unresolved, and we have dashed and queried such areas along the California coastline. Free–air gravity data are not presently available for the inner shelf between about 34 ½°N and 35 ¼°N.

The map is based on over 50,000 land stations and 30,000 sea stations, which are unevenly distributed (inset 1). Many of the areas with the greatest concentration of stations are from Ph.D. theses such as those by Corbato (1963) in San Fernando Valley, Biehler (1964) in the Salton trough, von Huene (1960) in Indian Wells Valley, and Greve (1962) on the San Francisco Peninsula. Data concentrated over Cenozoic basins have been obtained largely for commercial purposes. Although the southern San Joaquin Valley appears poorly controlled on the index to gravity coverage (inset 1), additional control in the form of one–mgal contour maps for much of this area was made available to us by oil companies, and we have used our own control to adjust the datum of such maps and have incorporated them into the state gravity map. (See Hanna and others, 1975a, for a more detailed discusson of the Bakersfield area.) The areas of poorest control on the map are the eastern San Bernardino Mountains, the Peninsular Ranges midway between Los Angeles and San Diego, parts of the southeastern Mojave Desert, and the east slope of the Sierra Nevada. Most of the gravity contours in northern California are controlled by a station spacing of 5 km or less.

Gravity Datum

Both the land and sea gravity data are on the Woollard and Rose (1963) gravity datum, which is based on an observed gravity value of 980118.8 mgal at the National Reference Base Station 0165–0 in Washington, D.C. (see Jablonski, 1974, p. 618, for a description of the National Base).

This datum is 0.8 mgal *higher* than the datum used until 1973 by the U.S. Departments of Commerce and Defense (Duerksen, 1949; Schwimmer and Rice, 1969; D.M. Scheibe, personal communication, 1978). The Woollard and Rose datum is 14.3 mgal to 14.7 mgal *higher* in California than the recently adopted International Gravity Standardization Net 1971 (IGSN 71) of Morelli (1974). The variation in datum is due chiefly to a difference in the fundamental calibration standard of gravity meters used to carry absolute gravity to California from the 1906 measurement in Potsdam, Germany, used by Woollard and Rose, and from eight 1965–1970 measurements in the United States, United Kingdom, France, and Colombia used by Morelli (1974, p. 97), the closest of which was at Denver, Colorado.

In November 1977, the first absolute measurement of gravity in California was made at San Francisco at Woollard and Rose's (1963, p. 41) Pendulum station GW54 in Golden Gate Park. The preliminary value there, corrected to floor level, is $979972.05 \pm .02$ mgal (Marson and Alasia, in press), which is 14.65 mgal *lower* than Woollard and Rose's pendulum measurement and 0.08 mgal *lower* than the adopted IGSN 71 value (Morelli, 1974, p. 48, station 12172–A).

The 1977 absolute measurement has been carried to the prime gravity base station A in Menlo Park (see appendix and figure 5) using one closed tie with three LaCoste and Romberg meters (R.C. Jachens, written communication, 1978). The average gravity difference (A – GW54) is -27.83 ± 0.01 (s.e.) mgal

[1] U.S. Geological Survey, Menlo Park, CA. 94025.

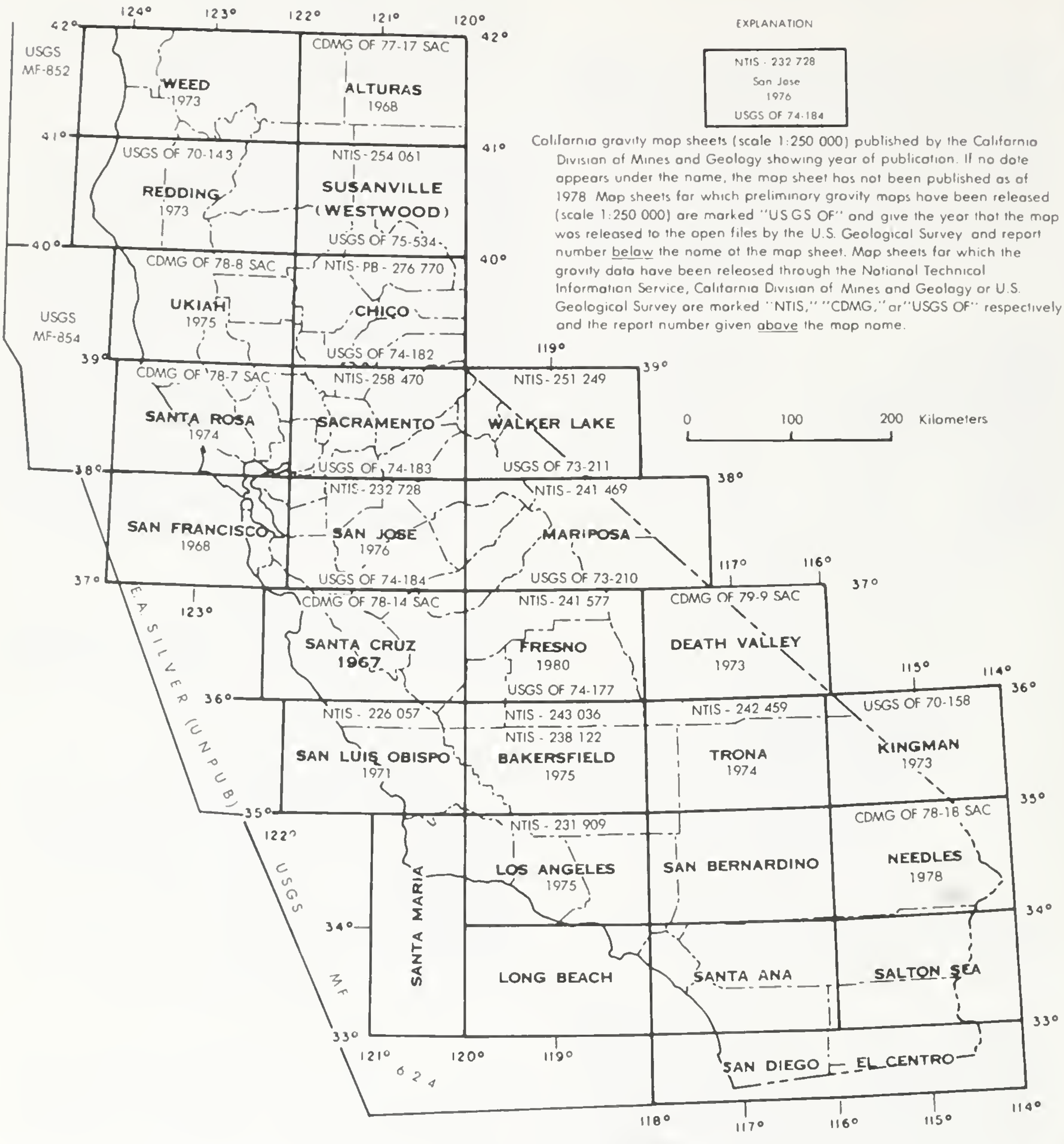

Figure 2. Index to gravity maps and published data used for compiling Gravity Map of California and Its Continental Margin. Unpublished preliminary compilation of five unpublished map sheets in southern California were provided by Shawn Biehler (written communication, 1977). An advance compilation of the Santa Maria sheet was made available by Jon Rietman (written communication, 1977). Gravity data for the San Francisco sheet are available from R.H. Chapman. Gravity data for the Weed sheet were compiled by Kim (1974, appendices 1 and 2). Table 1 keys map sheets and data indexed here to reports cited in references.

Table 1. Gravity map sheets and data indexed by area in Figure 2 and the corresponding author citations of reports in the references list or sources of unpublished maps.

QUADRANGLE	REPORT NUMBER IN FIG. 2	CITATION
Published Gravity Maps		
Alturas	1968	Chapman and Bishop (1968a)
Bakersfield	1975	Hanna and others (1975a)
Death Valley	1973	Chapman and others (1973)
Fresno	1980	Oliver and Robbins (1980)
Kingman	1973	Healey (1973)
Los Angeles	1975	Hanna and others (1975b)
Needles	1978	Chapman and Rietman (1978)
Redding	1973	Griscom (1973a)
San Francisco	1968	Chapman and Bishop (1968b)
San Jose	1976	Robbins and others (1976)
San Luis Obispo	1971	Burch and others (1971)
Santa Cruz	1967	Bishop and Chapman (1967)
Santa Rosa	1974	Chapman and Bishop (1974)
Trona	1974	Nilsen and Chapman (1974)
Ukiah	1975	Chapman and others (1975)
Weed	1973	Kim and Blank (1973)
Offshore 40°-42°N MF 852		Kososki and others (1977)
Offshore 38°-40°N MF 854		Kososki and others (1979)
Offshore 32 ½°-35°N MF 024		Vedder and others (1974)
Preliminary Gravity Maps		
Chico	74-182	Oliver and others (1974)
Fresno	74-177	Oliver and Robbins (1974a)
Mariposa	73-210	Oliver and Robbins (1973)
Sacramento	74-183	Oliver and Robbins (1974b)
San Jose	74-184	Robbins and Oliver (1974)
Susanville	75-534	Oliver and others (1975b)
Walker Lake	73-211	Oliver and others (1973)
Published Gravity Data		
Alturas	OFR 77-17 SAC	Chapman and others (1977a)
Bakersfield	243036	Robbins and others (1975a)
	238122	Hanna and Sikora (1974a)
Death Valley	OFR 79-9 SAC	Chapman (1979)
Fresno	241577	Robbins and others (1975a)
Kingman	70-158	Healey (1970)
Los Angeles	231909	Hanna and Sikora (1974b)
Mariposa	241469	Robbins and others (1975b)
Needles	OFR 77-18 SAC	Chapman and others (1977b)
Redding	70-143	Griscom (1970)
Sacramento	258470	Robbins and others (1976a)
San Jose	232728	Robbins and others (1974)
San Luis Obispo	226057	Burch and others (1974)
Santa Cruz	OFR 78-14 SAC	Chapman and Bishop (1978b)
Santa Rosa	OFR 78-7 SAC	Chapman (1978a)
Susanville	254061	Robbins and others (1976)
Trona	242459	Nilsen and Chapman (1975)
Ukiah	OFR 78-8 SAC	Chapman and Bishop (1978a)
Walker Lake	251249	Robbins and Oliver (1976)
Weed	Ph.D. thesis	Kim (1974)
Unpublished Maps		*Source*
San Bernardino		Shawn Biehler, 1978
Santa Ana		Shawn Biehler, 1978
Salton Sea		Shawn Biehler, 1978
San Diego–El Centro		Shawn Biehler, 1978
Long Beach		L.A. Beyer and Shawn Biehler, 1978
Offshore 35°–38°N		E.A. Silver, 1978

which provides an absolute value at Menlo Park A of 979944.22 ± 0.03 mgal at bench mark level. This value is 14.52 mgal lower than the value of 979958.74 mgal determined by Chapman (1966) relative to the Woollard and Rose datum. The difference between the comparisons at Golden Gate Park (−14.65 mgal) and Menlo Park (−14.52 mgal) of 0.13 mgal more likely represents an error in Woollard and Rose's (1963) pendulum measurement than an error in the later gravity meter ties.

Gravity Measurements and Reductions

Measurements of gravity differences in California have been made relative to 388 base stations established throughout the state relative to Woollard and Rose's (1963, p. 94) main control base WA 86 at San Francisco airport (Chapman, 1966; appendix). Most of the land measurements were made with LaCoste and Romberg gravity meters and are accurate to 0.1 mgal. Most of the offshore data were obtained with LaCoste and Romberg or Bell surface–ship gravity meters and are accurate to about 3 mgal. It was necessary to establish a number of mountain calibration loops to ensure the 0.1 mgal accuracy of the land data over the 1500–mgal gravity range in California (978.8 to 980.3 gals). For detailed discussions of the base stations, gravity meters used, and calibration problems, see the Appendix.

The approximately 50,000 gravity measurements on land were reduced to Bouguer anomalies assuming an average density of rocks above sea level of 2.67 g/cm³. The reductions include terrain corrections to a distance of 166.7 km from nearly all gravity stations. New techniques developed to expedite these reductions are summarized in the Appendix. The approximately 30,000 measurements at sea were reduced to free–air anomalies, and the formulas used are also given in the Appendix. The Bouguer anomalies on land are generally accurate to about 0.3 mgal but may be in error as much as 2 mgal in mountainous parts of the state. The offshore free–air anomalies have the same accuracy as the measurements, that is, about 3 mgal.

Reductions of both land and sea data are based on the Woollard and Rose (1963) gravity datum discussed above and on the 1930 International Gravity Formula (Swick, 1942, p. 61). Formulas for converting these data to the recently adopted IGSN 71 datum and the 1967 Gravity Reference System are developed in the Appendix. The conversion effect on free–air and Bouguer gravity anomalies within California and its continental margin varies gradually from −1.5 mgal at San Diego to about −3.2 mgal near the Oregon border (appendix, table 11). Thus, the net effect on the California gravity map would be to shift the contours by about half a contour interval.

Bouguer Gravity Anomalies and Average Elevations

As Bouguer himself recognized in about 1790, there is generally an inverse correlation between Bouguer gravity anomalies and topography. The correlation is improved if the topography is averaged over some radius in the range of 30 to 100 km, the radius for best correlation varying from province to province (Putnam, 1895; Mabey, 1960; Oliver, 1977). A comparison of a simplified version of the California gravity map (figure 3) and topography averaged to a radius of about 41 km (figure 4) shows a strong inverse correlation of approximately −1 mgal/10m or a little less than the attraction of an infinite sheet of 1.11 mgal/10 m of thickness (the simple Bouguer reduction factor). Thus the −30 mgal contour (figure 3) roughly correlates with the 300 meter contour (figure 4), the −60 mgal contour with the 600 meter contour, and so on. The incremental ratio of Bouguer anomalies to average elevations is not a constant but decreases at higher elevations above about 2000 m to about 0.8 mgal/10 because the corresponding compensating mass is deeper and the solid angle subtended is less (see section on the Sierra Nevada).

Departures of the Bouguer anomaly contours from those predicted by the average elevation contours are caused by inhomogeneities in the earth's crust and upper mantle. The interpretations of these inhomogeneities in terms of geologic structures make up the main body of this report.

Geomorphic Provinces and Scope of Report

Interpretations of the Bouguer gravity contours on land have previously been published for 16 of the 27 map sheets in California (figure 2). The major anomalies are here discussed by physiographic provinces with particular reference to the relation between Bouguer anomalies, average elevation (figure 4) and the major faults shown on the base map. Figure 5 shows the physiographic provinces used in this report.

Only minimal geologic summaries of the provinces are included in this report, and they are pointed toward possible variations in rock densities that might be expected to produce gravity anomalies. For more detailed geologic expositions of southern California, the reader is referred to Jahns (1954), and for northern California to Bowen (1962) and Bailey (1966). Oakeshott (1978) has most recently summarized the geology of the whole State, and Hamilton (1978) has summarized the outstanding structural problems from the point of view of plate tectonics. A simple Bouguer gravity map of the western United States west of 109°W (Eaton and others, 1978, plate 1) provides areal perspective for the major gravity features in California, but the map suffers from the lack of terrain corrections.

No attempt in this overview has been made to interpret all anomalies. All previously published gravity work has been summarized, and some new interpretations have been made to the extent possible without computer modelling. Some attempt has been made to call attention to anomalies of particular geologic interest where further work should be rewarding.

Acknowledgements

In addition to the authors who contributed various sections of this report, I wish to thank Francis Birch, G.P. Woollard and L.C. Pakiser, whose vision and initial encouragement in the early 1950s helped get regional gravity studies started in California; Ian Campbell and D.R. Mabey, who along with R.H. Chapman and myself in 1962 formulated the concept of and started planning toward the production of a gravity map for the whole state of California; P.M. Schwimmer, E.J. Hauer and Bob Iverson, who helped support and accelerate the California gravity program in 1968; and Shawn Biehler, J.D. Rietman, H.R. Blank, Jr., W.F. Hanna, D.L. Healey, S.H. Burch, J.F. Evernden, and Edward Byerly, all of whom later contributed considerable gravity data. The following staff members of the California Division of Mines and Geology helped obtain and reduce gravity data: Charles C. Bishop, Gordon W. Chase, Gary C. Taylor, Lydia Lofgren, and Gordon L. Campbell. Similarly, members of the

Figure 3. Gravity anomaly map of California with a contour interval of 30 mgal. This map is a reduction in both size and contour interval of the Gravity Map of California and Its Continental Margin (Oliver and others, 1980).

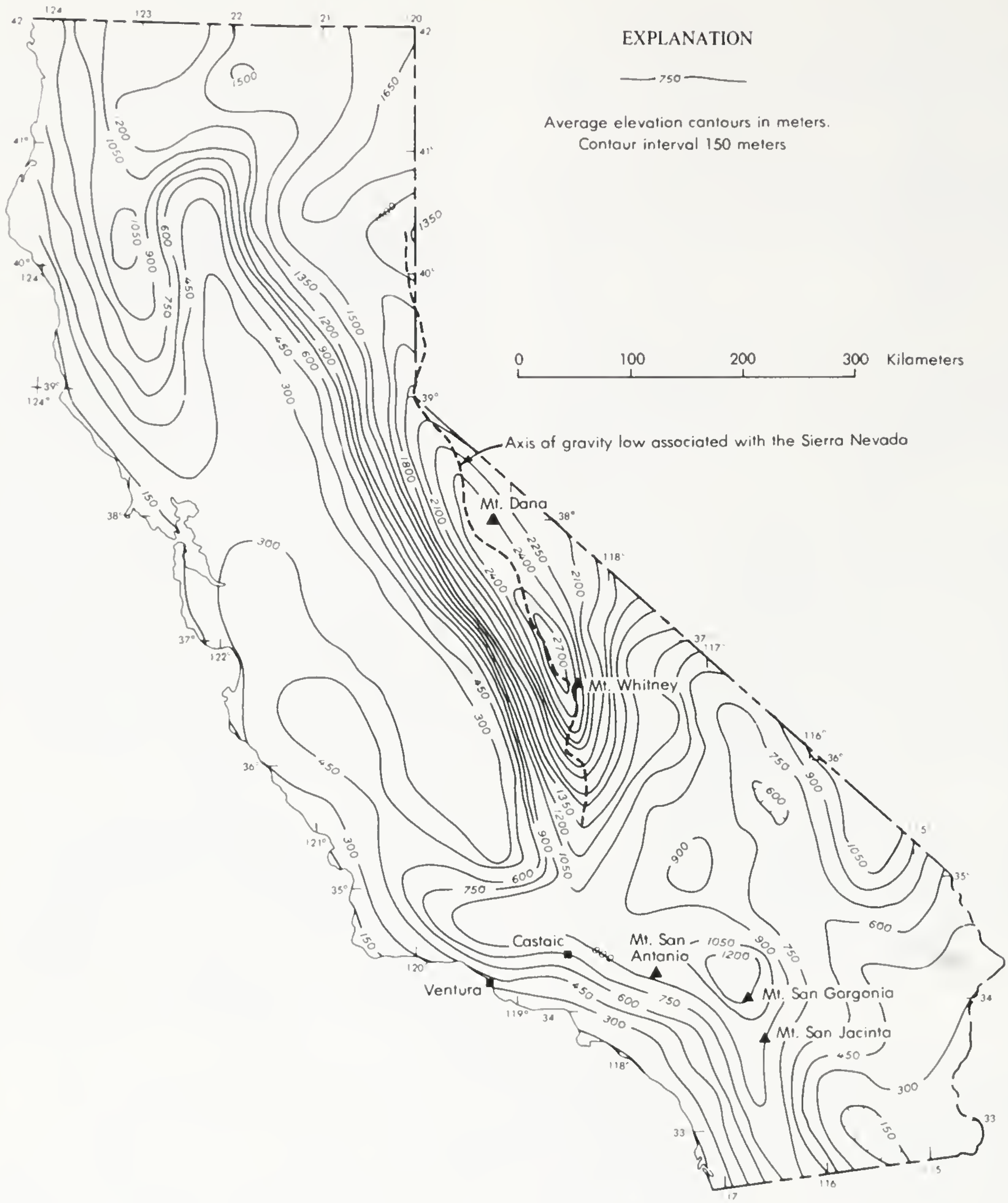

Figure 4. Generalized topography of California. Elevations have been averaged over rectangular blocks of three by three 15–minute quadrangles, the central quadrangle being weighted double. Dimensions of blocks are about 66 km by 81 km and have an area equal to that of a circle with a radius of about 41 km. Average elevations determined in this way have been plotted at the centers of each of the approximately 600 15–minute quadrangles in California and the data contoured. After James Gilluly (written communication, 1966) and Gilluly and others (1968, figures 10–15). Gilluly's original contour values in feet have been converted to meters using the approximation 1000 ft ~ 300 m. This approximation introduces an error of less than 2% to the contour values, which is within the uncertainty in their estimated values (± 100 m).

Figure 5. Relief map of California showing names and boundaries of physiographic provinces used in this report. From Bailey (1966, figure 1).

U.S. Geological Survey who contributed significantly are: R.F. Sikora, Victor McAllister, W.L. Rambo, Carter Roberts, R.C. Farewell, and Annabelle Kook. Field measurements were supported by the Defense Mapping Agency/Topographic Command (DMA/TC) under Project 3–68 and coordinated through T.H. Nilsen. Terrain corrections were supported by DMA/AC.

All the sections of this report have benefitted by review of J.E. Case and Warren Hamilton. Additional reviews of the offshore sections by David McCullough and Jack Vedder were most helpful. I wish to especially thank Andrew Griscom for helping edit the first draft of the manuscript and R.H. Chapman, who coordinated the contribution to the program by State agencies and several universities.

OFFSHORE SOUTHERN CALIFORNIA

by L.A. Beyer[1]

Physiography

The dominantly subsea geomorphic province between latitudes 32.5°N and 34.5°N and between the mainland and the Patton Escarpment is characterized by rugged and irregular topography. This is the northern part of the California Continental Borderland (Vedder, 1976). It is composed primarily of large submarine ridges and basins and smaller islands, banks, sea knolls, and ridges and valleys (Shepard and Emery, 1941; Emery, 1960). Slopes that connect basins and ridges are cut by numerous submarine canyons and gullies and range from gently convex upward to very steep (Moore, 1969). Elevations range from +746 m on Santa Cruz Island to –2,100 m in San Clemente Basin. Topographic relief from the highest elevation on Santa Cruz Island to the bottom of Santa Cruz Basin is 2,713 m (Vedder and others, 1974). The slope of the seafloor exceeds 20° in many locations, and late Cenozoic folds and faults frequently are expressed physiographically.

Geology

Vedder and others (1976b) described the complex late Cenozoic tectonic history of the California Continental Borderland as follows:

> The geologic evolution of the region is attributed to tectonic instability of the continental margin along the boundary between the Pacific and North American plates. As a result of right–lateral shear which began along the plate boundary about 30 m.y. ago, a network of ridge–and–basin structures developed. Rapid erosion of the ridges and thick accumulation of sediment in the basins accompanied by volcanism began about 20 m.y. ago. Subsequent deformation in response to continued right shear, which resulted in the formation of local en echelon zones of folds and faults, began about 12 m.y. ago and is continuing today.

Because pre–Miocene rocks have been subjected to this late Cenozoic tectonism and because mapping and sampling of submerged terrain is difficult, the geology of the borderland is poorly understood, especially south of the northern Channel Islands (San Miguel, Santa Rosa, Santa Cruz, and Anacapa).

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The part of the borderland that is north of the westward extension of the Santa Monica fault zone has a dominant east–west structural grain and is included in the Transverse Ranges Province (figure 5). The Santa Barbara Channel is the westward extension of the onshore Ventura Basin and is underlain by Cretaceous to Holocene sedimentary rocks and lesser thicknesses of Miocene volcanic rocks. The northern Channel Islands customarily are included in the Transverse Ranges Province, although J.G. Vedder (1978, personal communication) pointed out that late Cenozoic displacement along a westward extension of the Santa Monica fault zone may be spread among many small faults that curve northwestward and either die out or mostly lie north of the westernmost island. Howell and others (1978) also believe that pre–Miocene structures on the northern Channel Islands are similar to those south of the islands but that post–Miocene geologic features and geomorphology are analogous to those of the Transverse Ranges Province.

South of the northern Channel Islands, the borderland is customarily included in the Peninsular Ranges province because of its predominantly northwest–southeast structural grain. Although this region remains poorly understood, recent studies have greatly expanded our knowledge of subbottom structure, distribution of rocks on the seafloor, island geology, and areal distribution of gravity and magnetic anomalies, heat flow, and earthquakes (Vedder and others, 1974, 1976a,b,c; Greene and others, 1975; Howell, 1976; Taylor, 1976, Junger and Wagner, 1977; Nardin and Henyey, 1978; Blake and others, 1978). A generalized geologic map of the borderland is given in Figure 6, and a recently proposed subdivision of the area south of the northern Channel Islands into three structural blocks, based on distinctive types of basement and sedimentary cover, is summarized in Table 2. Table 3 summarizes characteristics of the Neogene depositional basins in the borderland and adjacent mainland.

Vedder and others (1974) described the general rock types included in the stratigraphic subdivisions of the generalized geologic map (figure 6). Basement rocks include: (1) the zeolite-bearing, Franciscan–like metasedimentary rocks and sepentinite dredged from localities west of the Santa Rosa–Cortes Ridge; (2) blueschist– and greenschist–facies rocks exposed on Santa Catalina Island and dredged from widely spaced localities; (3) metamorphosed mafic igneous rocks, mainly amphibolite and pyroxenite, exposed on Santa Catalina Island and dredged from the Patton Escarpment and the ridge between Santa Barbara and San Clemente Islands; (4) metamorphosed volcanic, sedimentary, and hypabyssal rocks exposed on Santa Cruz Island; and (5) silicic plutonic rocks exposed on Santa Cruz and Santa Catalina Islands. In some cases, dense Miocene volcanic rocks are effective basement in gravity and seismic interpretations.

Upper Cretaceous and lower Tertiary sedimentary rocks are mostly sandstone, siltstone, and claystone that in general have low porosities. These rocks are present along the Santa Rosa–Cortes Ridge, along the shelf just offshore from San Diego and presumably beneath the Santa Barbara Channel. The thickness of those strata is not well know, and their occurrence elsewhere in the borderland is uncertain.

Miocene volcanic rocks consist chiefly of andesitic and basaltic flows, flow breccia, tuff, and volcaniclastic rocks and are widely distributed over the borderland. Density varies widely

Bold dashed lines delineate tentative structural regions described in Table 2.

Figure 6. Generalized geologic map of the California continental margin off southern California (modified from Blake and others, 1978).

Table 2.—Tentative structural regions of California Continental Borderland south of the northern Channel Islands (Howell and others, 1978). Divisions based on samples taken from seafloor, seismic–reflection profiling, and geology of islands and mainland.

REGION	BOUNDARIES	BASEMENT ROCKS	SUPRABASEMENT ROCKS
I	Eastward from base of Patton Escarpment to northwest–trending lineament that approximately parallels the west slope of Santa Rosa–Cortes Ridge from Cortes Bank to near San Miguel Island.	Zeolite–bearing arenite and argillite with blocks of schist, mafic volcanic, and ultramafic rocks.	Late Oligocene and younger clastic and volcanic rocks fill sedimentary basins.
II	Eastward from Region I to a line that extends approximately along the west margin of San Clemente Island to the eastern part of the Santa Cruz Island fault.	Unknown except for basic plutonic rocks and greenstone exposed on Santa Cruz Island.	Thick sections of Cretaceous to Eocene clastic rocks are widespread and, locally, are overlain by marine and non–marine Oligocene sedimentary rocks, Miocene volcanic and volcaniclastic rocks, and correlative and younger rocks.
III	Eastward from Region II to the onshore part of the Newport–Inglewood fault zone; southeast of Newport Beach the eastern margin is uncertain.	Catalina Schist (blueschist–and greenschist–facies rocks with amphibolite and serpentinite) intruded and overlain by Miocene plutonic and volcanic rocks.	Locally thick sections of late Cenozoic clastic rocks overlie and butt against basement and volcanic rocks.

among these diverse volcanic rocks, making it difficult to evaluate their effect on the gravity field.

Miocene sedimentary rocks, chiefly claystone and siltstone, are widely distributed over the borderland. Pliocene and Quaternary rocks consist chiefly of semiconsolidated clay, silt, sand, and gravel and form relatively thick deposits on shelves and slopes near the mainland and in the basins. Miocene and younger sedimentary rocks are less dense than older sedimentary and basement rocks in the borderland, and low gravity field values usually are associated with significant accumulations of these younger rocks.

Previous and Present Gravity Studies

Early gravity mapping of the California Continental Borderland was a pioneering effort to evaluate and improve the performance of the surface ship gravity meter and to compile and analyze gravity measurements of variable precision (Caputo and others, 1963; von Huene and Ridlon, 1966; Harrison and La Coste, 1968). Harrison and others (1966) presented a regional Bouguer gravity map for much of the borderland and used a spatial filtering technique to separate anomalies into short–, intermediate–, and long–wavelength components. They concluded that short–wavelength anomalies due to upper crustal structure show a pronounced northwest–southeast strike, that intermediate–wavelength anomalies due to deeper structure are aligned east–west, and that long–wave length or regional Bouguer gravity decreases toward the northeast in response to a thickening of the crust. Von Huene and Ridlon (1966) presented regional free–air and Bouguer gravity anomaly maps of the Santa Barbara Channel and northern Channel Islands. They described a gravity maximum over the Channel Islands and an elongate gravity minimum that coincides with the westward extension of the Ventura Basin. Rietman and Aldrich (1969) discussed Bouguer anomalies of the north Channel Islands in terms of geologic structure of the islands and their platform.

The present free–air gravity anomaly map of the California Continental Borderland is an adaptation and update of the map published by Vedder and others (1974, sheet 7). This map is based almost exclusively on stable platform shipboard gravity surveys made since 1970 by the National Ocean Surveys of the National Oceanic and Atmospheric Administration (NOAA) and by the U.S. Geological Survey. Because of the strong influence of the rugged topography on the free–air anomalies in the borderland, parts of the discussion that follows are based on a Bouguer gravity map (figure 7) and unpublished regional and residual gravity maps prepared by me.

Regional Gravity and Crust–Mantle Structure

Regional Bouguer gravity in the borderland decreases toward the northeast at a rate of about 0.55 mgal/km. Harrison and others (1966) attributed this trend to a general thickening of the crust toward the northeast. The rate of decrease of Bouguer gravity appears to be slightly greater near the mainland than near the Patton Escarpment, possibly indicating that the crust is thickening more rapidly near the mainland or that crustal or upper mantle rocks become less dense toward the mainland. Seismic–refraction measurements suggest that the top of the mantle is at depths of about 18 to 21 km beneath Patton Ridge, 24 km beneath Catalina Basin, 29 km beneath Santa Monica Bay, and 30 to 32 km beneath the Los Angeles area and the Peninsular Ranges (Shor and Raitt, 1958; Roller and Healy, 1963).

The regional gravity trend is satisfied by a model of thickening crust toward the northeast based on these refraction data when densities of 2.95 g/cm^3 and 3.43 g/cm^3 are assumed for lower crustal and upper mantle rocks (Beyer and others, 1975). This model undoubtedly is too simple, but insufficient geophysical data exist to determine with confidence the finer structures of the lower crust and upper mantle beneath the borderland. The upper mantle velocity structure may be anomalous beneath the Trans-

Table 3. Selected Neogene depositional basins of the northern part of the California Continental Borderland and adjacent mainland (after Blake and others, 1978; Neogene thickness (max) modified by Crouch and Vedder, personal communication, 1980). Neogene thickness estimated from seismic reflection profiles.

Basin	Controlling Structure	Cross–Sectional Symmetry	Neogene Thickness (max., m)	Shape[1] in Pliocene Time	Strike of Long Axis (Pliocene Time)	Basin–Floor Substrata	Primary Sediment Source	Age of Inception
Unnamed basin west and southwest of TRASK KNOLL Patton	Graben?	Symmetric E–W	1800 ±	Elliptical	N20°W ±	Coastal Franciscan?	E?; hemipelagic	Post–Oligocene (?)
Patton	Downwarp	Symmetric E–W; slightly deeper on west	3500 ±	do.	N10°W ±	do.	W? hemipelagic	do.
Tanner	Graben	Asymmetric; deeper on east edge	1,500?	Irregular [2]	N25°W to N35°W	Paleogene strata?	?; hemipelagic	Post–early Miocene (?)
Santa Cruz[3]	Downwarp, faulted NE edge; faulted N end	Deepest in NW part; symmetric SW to NE	1,800–2,000	Rhomboid	N30°W to N45°W	Paleogene strata	N? and NE?; hemipelagic	Early to middle Miocene
San Nicolas[3]	Downwarp, faulted NE edge	do.	1,400 ±	Modified rhomboid	N30°W to N50°W	do.	NE? and NW?; hemipelagic	Middle Miocene
Santa Monica	Graben, N and SW margin faults	do.	3,500 +	Rhomboid	N50° to N75°W	Volcanic rocks and/or schist	NW	Late Miocene to Pliocene
Catalina	Graven NE and SW margin faults	Flat bottom; local deeps along SW edge	1000 ± (above volcanic rocks)	Rectangular or deltoid	N25°W to N45°W (curved)	do.	NE and SW?	Late Miocene (?)
San Pedro	Downwarp, median en echelon fault zone	Asymmetric; deepest in S or SW part	1,800 ±	Sigmoid	About N55°W (south of fault zone)	do.	NE?	Late Miocene to Pliocene
Gulf of Santa Catalina and San Diego Trough	En echelon faults		2,500 ±	Irregular[2]	N20°W to N40°W (N part) N30°W to N50°W (S part)	do.	NE	Middle Miocene
Los Angeles	Faulted downwarp	Symmetric E–W and N–S	8,000	Modified rhomboid or deltoid	N45°W	Paleogene rocks and/or schist	NE and E	Middle Miocene
Ventura	Graben	Asymmetric deeper in N	8,000	Cynoid	E–W ± 10°	Paleogene rocks and granite (E)	E and N	Late or middle Miocene

[1] Margins simplified to straight lines and/or smooth curves.
[2] Composite basins.
[3] Includes Santa Rosa–Cortes Ridge.

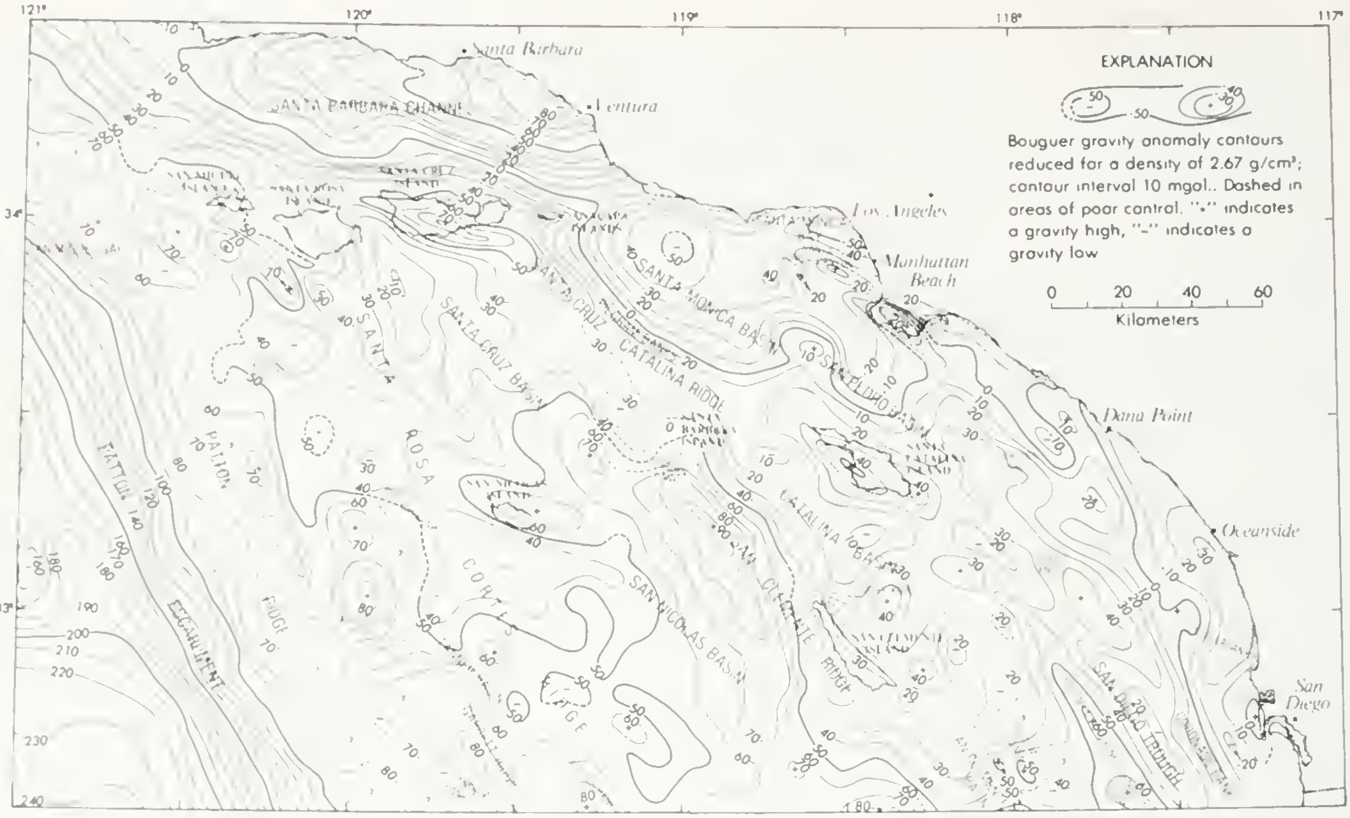

Figure 7. Bouguer anomaly map of the California Continental Borderland off southern California. Terrain corrections for marine gravity stations were made for ocean bottom topography extending from 3.5 to 99 km from each station. The seafloor closer than 3.5 km was assumed to be level and at the water depth of the staton. Terrain corrections for island gravity stations were determined to distance of 99 km and include the effect of submarine topography.

verse Ranges, according to P–delay time studies by Hadley and Kanamori (1977). Their P–delay time measurements made on borderland islands show intriguing variations of uncertain origin.

Short–wavelength free–air gravity anomalies generally correlate with the basin and ridge physiography of the borderland because they have not been adjusted to minimize the effects of topography. As a consequence, low free–air gravity anomalies usually occur over the basins and high free–air anomalies are associated with ridges and knolls. Bouguer gravity anomalies also partly reflect the basin and ridge physiography because the thicker accumulations of young, low–density rocks are found in the basins.

Santa Barbara Channel

The pronounced Bouguer gravity low that extends from Castaic through Fillmore and Santa Paula to the coast at Ventura is located over the eastern part of the Ventura Basin. This basin is estimated to contain more than 16,000 m of Cretaceous and Cenozoic sedimentary rocks near the town of Fillmore (Nagle and Parker, 1971). The elongate east–west trending Bouguer gravity low over the Santa Barbara Channel reflects the tectonic depression that forms the westward extension of the Ventura Basin. The deepest part of the Santa Barbara Channel gravity low is adjacent to the town of Ventura, where Cretaceous and Cenozoic rocks are estimated to be 11,000 to 13,000 m thick. The axis of the Bouguer gravity low which extends westward from Ventura, close to the mainland coast, presumably indicates the axis of maximum accumulation of sedimentary rocks in the channel. Bouguer gravity values increase gradually westward along the axis of the channel low, indicating a gradual decrease in the thickness of the sedimentary sequence toward the west. The closed free–air gravity low north of Santa Rosa Island corresponds to the bathymetric low in that area.

The Santa Barbara Channel is bounded on the north by the Santa Ynez Mountains, a homocline dipping steeply south that incorporates Cretaceous to Miocene rocks west of Santa Barbara and includes strata as young as Pleistocene east of Santa Barbara (Vedder and others, 1969). Bouguer gravity values increase northward from the channel into the Santa Ynez Mountains in response to the overall thinning of the sedimentary sequence in that direction and decrease eastward within the Santa Ynez Mountains primarily in response to an eastward increase in the thickness of young low–density sedimentary rocks.

Southward from the eastern part of the channel low, gravity increases toward the gravity high over Anacapa and Santa Cruz Islands. The westerly trend of this gradient is interrupted north of the western part of Santa Cruz Island by a ridge of high free–air and Bouguer gravity (lat 34°12'N, long 119°48'W) that extends north–northwest into the channel. A ridge in the basement probably is responsible for this anomaly, although Miocene volcanic rocks are known to occur at the edge of the island

platform north of the west end of Santa Cruz Island. The northwest–southeast trend of this anomaly distinguishes it from the east–west structural grain of the channel. Farther west the south flank of the channel low bends toward the northwest and appears to merge smoothly with the northwest-trending structural grain west of Point Arguello.

Northern Channel Islands

The general free-air and Bouguer gravity pattern over the northern Channel Islands and their platform results from the interaction of (1) the Santa Cruz Island gravity high, (2) the ridge of high gravity that extends from southwest of Santa Rosa Island to west of San Miguel Island, (3) the east–west–trending gradient that extends onto the island platform from the Santa Barbara Channel gravity low, and (4) the protrusion of the Santa Cruz Basin gravity low between Santa Cruz and Santa Rosa Islands (Rietman and Aldrich, 1969).

The elongate Bouguer gravity high over Santa Cruz Island is one of three large Bouguer gravity highs in the northern borderland. The others are over Santa Catalina Island and over San Clemente Ridge southeast of Osborn Bank. The Santa Cruz Island high is centered over Jurassic schist exposed on the south side of the Santa Cruz Island fault (Hill, 1976; Rietman and Aldrich, 1969). This gravity high extends west–northwest of the island for about 15 to 20 km and to the east of the island where, following bathymetric ridges, it splits into two lobes or ridges. One ridge extends east, paralleling mapped faults, through Anacapa Island and east–northeast to join the gravity high of the western Santa Monica Mountains. The other ridge, which has more positive Bouguer gravity, turns southeast along the north end of the Santa Cruz–Catalina Ridge. Although Miocene volcanic rocks, especially volcanic centers with pipes, also contribute to the Santa Cruz Island gravity high, the narrow band of highest gravity that extends offshore reflects Jurassic basement that abuts the south side of the Santa Cruz Island fault. Relatively high Bouguer gravity values that extend from Santa Cruz Island over the north end of Santa Cruz–Catalina Ridge suggest that basement also remains relatively shallow at the north end of this ridge.

High pressure–low temperature rocks of the blue amphibole facies, similar to some of the metamorphic rocks exposed on Santa Catalina Island, have been recovered from the submarine ridge south of Santa Rosa Island (Vedder, 1976; Platt, 1976). This submarine ridge (lat 33°50'N, long 120°11'W) is near the southeast end of the elongate free–air and Bouguer gravity high that extends northwest to west of San Miguel Island. This elongate high presumably reflects a ridge of Mesozoic basement rocks, possibly with Miocene volcanic rocks. The north eastward decrease of gravity from this ridge through San Miguel and Santa Rosa Islands suggests that basement dips gently northeast toward the Santa Barbara Channel. Basement rocks presumably are at a greater depth beneath Santa Rosa Island than beneath San Miguel Island. Immediately south and southwest of Santa Rosa Island and north of the ridge of high gravity, a trough of low Bouguer gravity (lat 33°53'N, long 120°10'W) coincides with a narrow faulted syncline that appears from seismic profiles to contain late Cenozoic rocks. Another poorly controlled Bouguer gravity low (not shown on map) immediately south of the channel between Santa Rosa and San Miguel Islands and a trough of slightly lower gravity (lat 34°N, long 120°25'W) immediately south of San Miguel Island may be related to the projected westward extension of the Santa Rosa Island fault.

North of Santa Rosa Island and northeast of San Miguel Island, the slight southward embayment of lower gravity onto the island platform suggests that a thicker sequence of relatively low density pre–Pliocene strata may be present there. This area, together with Santa Rosa Island, may be the location of a northwest–trending basement trough between the basement high southwest of Santa Rosa and San Miguel Islands and the basement high of Santa Cruz Island. North and west of San Miguel Island, the trend of the gravity contours follows the northwesterly strike of mapped faults. The regional gravity high over the northern Channel Islands may extend northwest to Arguello Canyon.

The Santa Cruz Basin gravity low, which extends over the extreme east end of Santa Rosa Island and into the passage between Santa Rosa and Santa Cruz Islands, is apparently due to a thicker sequence of sedimentary rocks in this area; it also appears to be structurally controlled by faulting along its eastern margin. Small gravity features on the Channel Islands that reflect the local geology are discussed by Rietman and Aldrich (1969).

Inner Basins and Ridges

The Bouguer gravity high centered over the Palos Verdes Peninsula extends northwest to a point about 20 km west of Manhattan Beach, indicating a northwestward extension of the Palos Verdes uplift to the east edge of Santa Monica Canyon. North of Santa Monica Canyon the saddle between the gravity lows over Los Angeles and Santa Monica Basins coincides with the Dume embayment (Junger and Wagner, 1977). The Dume embayment, one of the main routes for sediment transport into Santa Monica Basin during Pliocene time, may be underlain by as much as 500 to 1,000 m of post–Miocene strata.

The Bouguer gravity high over the Palos Verdes Peninsula appears to be the north end of a ridge of high gravity that extends southeast beyond Crespi Knoll toward Coronado Bank, and presumably reflects the presence of a basement ridge. There are several Bouguer gravity lows between this ridge of high gravity and the mainland. The oval gravity low east of Lausen Knoll, situated principally between the southeast extensions of the Palos Verdes and Newport–Inglewood fault zones, is located over a small basin or graben. Seismic–reflection profiles suggest that this basin has at least 1,500 m of post–Miocene strata (Junger and Wagner, 1977). Steep gravity gradients along the northeast and southwest margins of this low coincide with mapped faults. Vedder and others (1976b) believe that as much as 5,500 m of late Mesozoic and Cenozoic rocks may be present on the inner shelf east of the Newport–Inglewood fault zone near Dana Point, but these rocks probably do not extend offshore far enough to contribute to this gravity low.

Another Bouguer gravity low extends from west of Oceanside south through the lower reaches of La Jolla Canyon to the structurally controlled submarine valley between the Coronado Bank and San Diego shelf gravity highs. Cretaceous and (or) Cenozoic strata up to several thousand meters thick may be present beneath parts of this gravity low, especially straddling the inner shelf break west of Oceanside and immediately beyond the inner shelf break west of La Jolla Canyon. As much as 1,500 m of Upper Cretaceous and Paleogene sedimentary rocks are thought to be present on the San Diego shelf (Vedder and others, 1976b) and to extend a short distance offshore between San Diego and Dana Point. Miocene and younger sedimentary rocks

are exposed on Coronado Bank, which is a broad, nearly symmetrical anticlinal structure (Vedder and others, 1976b).

The free-air and Bouguer gravity lows over the Santa Monica Basin are centered over the thickest accumlation of post-Miocene sediments in the basin. Junger and Wagner (1977) estimated from seismic profiles that this post-Miocene sequence is 3,500 m thick. Steep gravity gradients along the north margin of the basin coincide with the offshore extension of the Santa Monica fault and the Malibu Coast fault. A long linear gradient coincides with the southwest margin of the Santa Monica basin. Seismic profiles indicate that the southwest margin of the basin also is faulted. The free-air and Bouguer gravity lows over the San Pedro Basin also coincide with the thickest accumulation of post-Miocene sediments in the basin; Junger and Wagner estimate that there is 1,800 m of post-Miocene rocks in the San Pedro Basin.

Free-air and Bouguer gravity lows over the San Diego Trough are located over the eastern part of the trough against the slope that leads up to Coronado Bank. Maximum accumulation of post-Miocene rocks is about 1,000 m in the northwest end of the trough and about 600 m in the southeast end (J.G. Vedder, written communication, 1978). This distribution of post-Miocene rocks cannot fully account for the Bouguer anomaly, which in part must be due to an eastward-thickening sequence of relatively less dense older sedimentary or basement rocks. The elongate Bouguer gravity low over the San Diego Trough extends northwest and joins an arm of low Bouguer gravity that extends southeast from the Catalina Basin. A basement trough probably coincides with this trend of low Bouguer gravity.

The free-air and Bouguer gravity lows in the Catalina Basin correspond to about 600 m of post-Miocene sedimentary rocks. Faults bounding the Catalina Basin are expressed as steep free-air and Bouguer gravity gradients although there is not a steep Bouguer gravity gradient associated with the San Clemente fault adjacent to San Clemente Island and the San Clemente Basin. The San Clemente fault may not juxtapose rocks of significantly different densities in this area. The Bouguer gravity high over Emery Knoll supports the contention that the knoll is either a local basement high underlain by a shallow intrusive body or a volcanic dome with a volcanic pipe or shallow intrusive body.

The narrow elongate Bouguer gravity high over Thirtymile Bank, where Miocene volcanic and basement rocks have been dredged, supports the contention that this ridge is a fault-bounded basement high. A relatively thin sequence of Miocene sedimentary rocks cover Fortymile Bank and Boundary Bank.

The Bouguer gravity high over Santa Catalina Island is centered over Jurassic basement rocks that, judging from the shape of the gravity high, extend northwest and southeast of the island. Saddles in the Bouguer gravity high along Santa Cruz-Catalina Ridge between Santa Cruz Island and Pilgram Banks and between Pilgram Banks and Santa Catalina Island presumably indicate basement lows and may indicate greater accumulations of sedimentary rocks.

A pronounced Bouguer gravity high extends southeast from Osborn Bank to west of San Clemente Island. Lobes of this gravity high extend north, northwest, and west of Osborn Bank to include Santa Barbara Island, the southern part of the Santa Cruz Basin, and the San Nicolas Island platform. Metamorphosed mafic igneous rocks have been dredged from the San Clemente Ridge near the center of this high, and basement rocks presumably occur at relatively shallow depths over much of the surrounding region.

Outer Banks and Ridges

The gravity lows over the Santa Cruz and San Nicolas Basins are located over the northwest ends of the basins on the free-air gravity map and, on Bouguer maps, are located even farther northwest. In the San Nicolas Basin the greatest accumulation of post-Miocene strata is in the northwest part of the basin, where seismic profiles suggest that 1,200 m of sediment are present. Pre-Miocene sedimentary rocks dip beneath the basins from the Santa Rosa-Cortes Ridge and presumably contribute to the displacement of the gravity lows from the bathymetric centers. These pre-Miocene rocks are believed to wedge out near the bases of the slopes that form the eastern margins of these basins.

The Santa Rosa-Cortes Ridge is believed to be underlain by as much as 5,000 m of Cretaceous to Holocene sedimentary rocks in the north and as much as 3,500 m of Cretaceous to Miocene rocks at its south end on Cortes Bank. An outer continental shelf stratigraphic test (OCS-CAL 75-70 No. 1) drilled at latitude 32°26'05"N, longitude 118°59'49"W on Cortes Bank to a depth of 3,328 m penetrated mostly shale and sandstone ranging in age from Upper Cretaceous (Cenomanian) to middle Miocene (Luisian) (Paul and others, 1976). Basalt flows 183 m thick were penetrated at a depth of 695 m. Eocene sedimentary rocks are exposed on San Nicolas Island. Embayments of low gravity extend onto the ridge from the Santa Cruz and San Nicolas Basins north and south of San Nicolas Island, possibly indicating greater thicknesses of sedimentary rocks in these areas.

The area west of the Santa Rosa-Cortes Ridge is very poorly understood. Gravity lows over the Tanner Basin correspond well with accumulations of post-Miocene sedimentary rocks. A thickness of about 1,000 m of these rocks is believed to be present in the southern part of the Tanner Basin from seismic profile estimates, and gravity data suggest that more than this thickness may be present in the northern part of the Tanner Basin. Jurassic basement has been dredged from Albatross Knoll, and Bouguer gravity suggests shallow basement on Nidever Bank also. To the southeast, lower Bouguer values over Garrett Ridge and Hancock Bank suggest that these features are underlain by rocks less dense than the Jurassic basement; this also appears to be true for Trask Knoll to the northwest.

Patton Ridge is bounded on the west by the long straight free-air and Bouguer gravity gradient associated with the Patton Escarpment. On the east, Patton Ridge is bounded by a straight free-air and Bouguer gradient that extends about 100 km south-southeast from Trask Knoll and coincides with a topographic lineament and structural downwarp. Vedder and others (1976b) believe that Patton Ridge may be underlain by pre-late Cretaceous igneous, sedimentary and metamorphic rocks, partly intruded and overlain by Miocene volcanic rocks. Pliocene(?), Miocene, and some Oligocene sedimentary rocks have been dredged and cored from Patton Ridge. Embayments of low Bouguer gravity extend over Patton Ridge west of Albatross Knoll and west and southwest of Trask Knoll. These areas of lower Bouguer gravity values coincide with regions that have a thin cover of post-Miocene sediment; these lower values may in part indicate relatively thicker sections of pre-Pliocene strata beneath.

Patton Ridge is bounded on its east side by a downwarp that leads into an elongate north–northwest–trending basin informally called Patton basin. A thick section (> 1,200 m) of post–Miocene and Miocene rocks appears to underlie the north end of this basin immediately south of Trask Knoll. At the north end of Patton Ridge, the free–air and Bouguer gravity lows directly east of San Miguel Gap coincide with a small basin that, from seismic profiles, appears to contain late Cenozoic sediment.

Harrison and others (1966) conclude that the long straight gravity gradient associated with the Patton Escarpment reflects the rapid eastward thickening of the crust from about 8 km west of Patton Escarpment to about 20 km at the top of the escarpment. They believe that the boundary between the mantle and crust dips steeper than 45° beneath Patton Escarpment. The free–air gravity lows at the base of Patton Escarpment are largely artifacts of the gravitational effects of the slope and the rapidly thinning crust and do not necessarily indicate significant accumulations of low–density material at the base of the slope.

TRANSVERSE RANGES

by H. W. Oliver[1]

Physiography and Geologic Setting

The Transverse Ranges trend west, transverse to the north to northwest tectonic grain of California (figure 5) and, indeed, of the entire west coast of North America. The main ranges are the San Gabriel Mountains north of Los Angeles, the San Bernardino and Little San Bernardino Mountains to their east, the Santa Monica Mountains west of Los Angeles, and the Santa Ynez Mountains north of Santa Barbara. The San Bernardino Mountains are the highest range and culminate in Mount San Gorgonio (3502 m, 11,502 ft), the highest point in southern California. The highest point in the San Gabriel Mountains, Mount San Antonio, is almost as high (3067 m, 10,064 ft) although the average elevation of these mountains is about 300 m (1000 ft) less than the 1200 m (4000 ft) value for the San Bernardino Mountains (figure 4). The Transverse Ranges include two major onshore basins: the San Fernando Valley northwest of Los Angeles, and the Ventura Basin just south and east of Ventura. Santa Cruz, Santa Rosa, and San Miguel Islands constitute an offshore extension of the Transverse Ranges, but the discussion of their gravity features is included in the section on Offshore Southern California.

Both the San Gabriel and the San Bernardino Mountains are made of Precambrian and Paleozoic metamorphic and plutonic rocks and of Mesozoic granitic rocks (Jennings and others, 1977). The San Gabriel Mountains include an extensive anorthosite complex south of Palmdale. The ranges west of Los Angeles consist of folded Cretaceous and Cenozoic strata.

Structurally, the San Gabriel Mountains form part of what Bailey and Jahns (1954) regard as a "gigantic horst," although the structure is not a simple extensional feature like those in the Great Basin (see section on that area). The mountains are bounded on the south by the Sierra Madre fault zone, which is a high–angle reverse fault that dips north beneath the mountains. The San Andreas fault bounds the San Gabriel Mountains on the north and passes obliquely between the San Gabriel and San Bernardino Mountains without apparent offset of the east–west topography, in spite of its horizontal dislocation of 250 km since Cretaceous time (Crowell, 1973).

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Regional Gravity

Aside from the effect of sediments and other unusually high or low density rock units, Bouguer gravity contours over the Transverse Ranges are similar to the average elevation contours (figure 4), indicating that the ranges are in regional isostatic balance. The ratio between the change in Bouguer gravity anomalies to change in regional elevation is about 1 mgal/10 m, the same as that for the Great Basin (see table 5). The data in Table 4 are critical to this argument and were obtained by placing a 1:750,000 clear film enlargement of Figure 4 on a 1:750,000 clear film copy of the gravity overlay, and both overlays on the 1:750,000 scale geologic map of California (Jennings and others, 1977). The geologic base is better than the fault base for this purpose because it shows which gravity contours are clearly associated with some unusual rock unit and therefore are not representative of regional gravity. For example, the range of Bouguer anomalies of –80 to –110 mgal along the 900–meter average elevation contour (table 4) is taken primarily on Mesozoic granite, and the local anomalous values associated with Precambrian anorthosite and schist have been avoided. Gravity values do appear to decrease slightly to the southeast along the average 900–meter contour toward the San Bernardino Mountains, where the –110 mgal value occurs.

Table 4. Comparison between average elevations and regional Bouguer anomalies in the Transverse Ranges.

Average elevation (meters)	Location	Range in Bouguer anomalies (mgal)	Average Bouguer anomaly (mgal)
300	Santa Monica Mountains	–10 to –50	–30
600	South boundary of San Gabriel Mountains	–60 to –70	–65
900	Arcadia to Saugus, 6 km south of and parallel to north boundary of San Gabriel and southwest boundary of San Bernardino Mountains	–80 to –110	–95
1200	North–central San Bernardino Mountains	–115 to –125	–120

The conclusion that the Transverse Ranges are in regional isostatic equilibrium is seemingly contradicted by seismic evidence that there is no distinct "isostatic" crustal root beneath the Transverse Ranges (Roller and Healy, 1963; Mellman, 1972; Hadley and Kanamori, 1977). Actually, the average elevation, as defined by the method used to derive Figure 4, along the highest part of the San Gabriel Mountains near Mount San Antonio is only 700 m (3000 ft), and the average elevation continues to rise well out into the Mojave Desert in spite of the local decrease in elevation at the northern boundary of the San Gabriel block. Bouguer anomalies also continue to decrease northward from about –90 mgal over the north flank of the San Gabriel Mountains to about –105 mgal over bedrock near Hi Vista in the Mojave Desert before starting to increase again in

accordance with the decreasing elevation (figure 4). Thus a local root under the San Gabriel Mountains is not required for regional isostatic equilibrium. However, a regional mass deficiency under the higher southwestern part of the Mojave Desert and higher northern edge of the Transverse Ranges is defined by the region of gravity anomalies at stations on bedrock with values less than −90 mgal. This area includes the San Andreas fault and is difficult to visualize on the gravity map but corresponds approximately to the elongate area with an average elevation greater than 900 m (figure 4). The mass-deficient area is very similar to the elliptical area centered near Palmdale (lat 34°42′N, long 118°7′W), which has sustained a historic rise of 30 to 45 cm (Castle and others, 1976; U.S. Geological Survey, 1977) and may be related to it.

The gravity and regional elevation data suggest that the thickness of the crust is about 3 km thicker under the northern part of the San Bernardino Mountains than under the San Gabriel Mountains within the closure of the −125 mgal contour, or perhaps more accurately the 1200 m average elevation closure. This calculation assumes a crust-mantle density contrast of 0.3 g/cm^3, the same value which was required to reconcile gravity and seismic data in the Sierra Nevada (Oliver, 1977, figure 4). The expected delay in P_n arrivals caused by a 3-km crustal thickening is about 0.2 second, and such delays were recorded at two stations on the east side of the San Bernardino Mountains from a magnitude 4.5 earthquake (Hadley and Kanamori, 1977 figure 3).

According to the most recent seismic evidence (Hadley and Kanamori, 1977, figure 3), the crust-mantle interface, as defined by the transition of 6.7 to 7.8 km/s material, rises slightly from a depth of about 32 km under the San Gabriel Mountains to a depth of about 30 km under the San Bernardino Mountains, the reverse of the apparent Bouguer anomaly trends. However, the eastward rise is accompanied by a 3-km thickening of a 6.2 km/s upper layer at the expense of the 6.7 km/s lower crustal layer. The seismic evidence is poorly controlled in the vicinity of the San Bernardino Mountains, but it suggests that the extra 300 m of average elevation there may be partly compensated by an unusually great thickness of light rocks (6.2 km/s—granite?) within the upper crust.

Compensation of the San Gabriel Mountains is further complicated by the presence of a high-velocity ridgelike structure within the upper mantle directly beneath the mountains interpreted from early p-wave arrivals (Hadley and Kanamori, 1977, figure 4). The ridge rises from a depth of over 100 km under the northern Mojave Desert to a depth of 40 km under the San Gabriel Mountains and then drops off southward to depths of about 70 km under the Peninsular Ranges. The velocity within the proposed ridge is 8.3 km/s or 0.5 km/s higher than the surrounding upper mantle. Hadley and Kanamori estimate that the associated density contrast is in the range 0.03–0.15 g/cm^3 and that the expected gravity effect of the proposed upper mantle structure is a 30- to 150-mgal high centered near Cajon Pass and striking about N45°E. The gravity map does not contain such a feature, although a broad lower amplitude anomaly of less than 15 mgal might be difficult to recognize.

Basin Anomalies

Very strong gravity lows occur over both the Ventura Basin (lat 34°21′N, long 119°15′W) and San Fernando Valley (lat 34°20′N, long 118°27′W) and have been assessed previously by Hanna and others (1975b) and by Corbato (1963), respectively.

The series of gravity lows between Ventura and Castaic (lat 34°30′N, long 118°36′W) marks the axis of the elongate Ventura basin,which is a highly folded synclinorium containing an estimated 15 km of Cenozoic sedimentary rocks (Bailey and Jahns, 1954). The basin extends westward into the continental borderland as marked by the closures of the −80 mgal and −70 mgal contours in the Santa Barbara Channel (see section on Offshore Southern California). The decrease in Bouguer anomalies of −80 to −105 mgal along the axis of the gravity minimum between Ventura and Castaic should not be interpreted as indicating greater thicknesses of sediment toward Castaic. A regional eastward decrease in gravity affects values in the ranges as well, and this can be estimated from the State average elevation map (figure 4). The average elevation of Castaic is about 750 m and that of Ventura is about 400 m. Using the ratio of gravity difference to average elevation difference of −0.1 mgal/m (table 4), the estimated regional gravity difference is (0.1) (750–400) = 35 mgal lower at Castaic. Correcting the −105 mgal gravity values for regional gravity indicates that the residual gravity level at the gravity minimum near Castaic is really about −70 mgal, 10 mgal higher than the gravity minimum of −80 mgal at Ventura. The maximum gravity closure associated with the Ventura basin is difficult to determine because gravity values in the Santa Monica Mountains to the south (+10 mgal) are higher than in the Santa Ynez Mountains to the north (−60 to −40 mgal). By again using the elevation information in Figure 4, the isostatically corrected residual anomaly at Ventura is $-80 + -(-0.1(400) \sim -40$ mgal, and this value represents the net perturbation in "normal gravity" caused by the Ventura basin. Similarly, the average elevation at the center of the Santa Monica Mountains gravity high is about 200 m, so the departure from normal gravity there is about +30 mgal.

Bouguer gravity anomalies over San Fernando Valley are as low as about −90 mgal just south of the San Fernando fault zone, along which movement occurred in 1971. The residual closure associated with the valley is about 45 mgal and has been attributed to upper Cenozoic sedimentary rocks about 4.5 km thick (Corbato, 1963). Remeasurements of Corbato's gravity measurements after the 1971 earthquake indicated changes of up to +0.45 mgal north of the fault zone, reflecting the uplift of as much as 2 m there (Oliver and others, 1975a).

Relation to Faults

The gravity expression of the San Andreas fault is small where it passes through the Transverse Ranges. No anomalies or patterns are obviously offset by the fault. Of course, if Crowell's (1962) figure of 250 km right-lateral movement since Cretaceous time is approximately correct, the pre-Cenozoic rocks which were once continuous with those on the northeast side of the fault in the Mojave Desert and San Bernardino Mountains are now located on the southwest side of the fault east of San Luis Obispo. The low gravity relief in the southwest Mojave Desert is similar to low relief patterns east of San Luis Obispo, but it is difficult to single out any particular anomaly that matches up on both sides of the fault. The effects of crustal structure would be quite different in the two areas and would tend to camouflage the respective gravity effects of offset geologic units.

Similarly, the rocks exposed on the southwest side of the San Andreas fault where it passes through the northeast flank of the

San Gabriel Mountains are located on the northeast side of the fault northeast of the Salton Sea. Specifically, the northern part of the gravity high (–60 mgal contour) over the Sierra Pelona (lat 34°33'N, long 118°26'W) occurs over the type locality of the Pelona Schist. The local amplitude of the anomaly is about 20 mgal. Discussion of a similar gravity high on the opposite side of the San Andreas fault in the Salton Trough is included in that section along with an analysis of its relevance to offset on the San Andreas fault.

Another gravity high appears to be associated with the Pelona Schist about 20 km east of Redlands (lat 34°3'N, long 116°55'W). The center of the high is over rocks mapped as mylonitic gneiss by Dibblee (1964), and this gneiss has been thrust over the Pelona Schist at two nearby localities both west and east of the central outcrop and within the gravity high (Rogers, 1969). Thus, the Pelona Schist is autochthonous and probably underlies much of the gravity anomaly. The anomaly has an amplitude of about 30 mgal and its shape is poorly determined (inset 1; Oliver and others, 1980). Apparently, the schistose bodies east of Redlands and at Sierra Pelona are either much thicker or contain a denser facies than other bodies that crop out in the Transverse Ranges (see Haxel and Dillon, 1978, figure 2; Rogers, 1969). The gravity high east of Redlands also occurs directly on the South Branch of the San Andreas fault. Because the sources of gravity anomalies are directly below the anomalies, this feature raises questions concerning the likelihood of extensive strikeslip movement on the South Branch. Detailed gravity measurements along the South Branch west of Redlands indicate that the buried fault scarp is located 200 to 300 m south of the exposed mountain front (Dana, 1968, 1970).

The gravity expression of the San Jacinto fault is particularly impressive near San Bernardino (lat 34°5'N, long 117°22'W) where a gravity step of 30 to 40 mgal occurs across the fault, the high side being on the southwest. Another gravity step of about 30 mgal lies across the Santa Monica fault between San Monica and Glendale. East of Glendale, the linear gravity gradient bends to the south and seems to reflect the northwest–striking pre–Quaternary faults shown on the base map. The Raymond fault between South Pasadena and Arcadia does not have a gravity expression, but the Sierra Madre fault zone east of Arcadia to Upland has a step of 5 to 10 mgal, the gravity field being down on the south side of the fault.

The San Gabriel fault slices through bedrock between San Fernando and Pyramid Lake (lat 34°40'N, long 118°40'W) and a small eastward rise in gravity signals the eastern terminus of the Ventura Basin anomaly; but north of Pyramid Lake, the correlation is excellent between the San Gabriel fault and a gravity gradient that reaches 8 mgal/km. Where the fault approaches the Frazier Mountain area and the San Andreas fault, the gravity gradient bends toward the north away from the surface fault trace, indicating the probable location of the major displacement at depth.

The Santa Ynez fault is a reverse fault that is steep near the surface and that may have some left–lateral motion (Bailey and Jahns, 1954). The fault dips steeply south and the rocks on the south side have been upthrown 1 ½ to 3 km on the north flank of a west–trending anticline that controls the topography of the Santa Ynez Mountains. An east–plunging gravity nose with a residual amplitude of 20 to 30 mgal is associated with the anticline, and a significant gravity gradient is coincident with the fault northwest of Santa Barbara in the vicinity of Lake Cachume (lat 34°35'N, long 119°55'W). About 10 km west of the lake, the fault branches, and the south branch has apparently been active in Quaternary time (Jennings, 1975). However, the major gravity gradient marks the north branch of the fault which continues west (Jennings and others, 1977). East of Lake Cachume, the associated gravity step decreases in magnitude, suggesting that the throw on the fault decreases proportionately.

PENINSULAR RANGES

by H.W. Oliver[1]

Topography and General Geology

The Peninsular Ranges of southwestern California (figure 5) make up the northern part of a larger geologic province that extends 1100 km south to the tip of Baja California (Jahns, 1954). The ranges form the backbone of southern and Baja California and culminate in Mount San Jacinto (3293 m, 10,805 ft.) located in the northeast corner of the province (33°49'N, 116°39'W). The highest mountains are along the east side of the province and form a ridge that is nearly in alignment with the crest of the Sierra Nevada (figure 5). Spectacular scarps 2 to 3 km high are disposed en echelon along the east face of the Peninsular Ranges and bear a striking resemblance to the eastern scarps of the Sierra Nevada.

The ranges are made chiefly of Cretaceous granitic rocks that constitute the southern California batholith (Larsen, 1948; Morton and Gray, 1971; Budnik, 1972). The age of the batholith ranges from about 120 million years on the west to about 105 million years on the east based on concordant biotite and hornblende K–Ar dates and limited control with zircon ages (Banks and Silver, 1966; Evernden and Kistler, 1970; Krummenacher and others, 1975). Initial Sr^{87}/Sr^{86} ratios increase from west to east, reaching continental values of 0.706 near Mount San Jacinto (Kistler and Peterman, 1973; Kistler and others, 1973). Thus, the southern California batholith is similar in some respects to the Sierra Nevada batholith, but it is slightly more mafic, the average composition being tonalite (Larsen, 1948; see Bateman and others, 1963, for comparative data). About 15 percent of the batholith west of the Elsinore fault consists of a myriad of gabbroic bodies (Jennings and others, 1977) whereas the area east of the San Jacinto fault is free of mafic bodies and generally more felsic. Density measurements of the southern California batholith are not available but, judging from the petrographic descriptions (Larsen, 1948), must vary from about 3.0 g/cm³ for the gabbros to 2.6 g/cm³ for the leucogranites (see Oliver and Robbins, 1980, for comprehensive density data of granitic rocks).

Paleozoic and Mesozoic metamorphic rocks make up the wallrocks and the roof pendants that project into the batholith. The western wallrocks are chiefly low–grade slate and greenstone whereas the roof pendants include graywacke quartzite, marble, and some andalusite–sillimanite–facies rocks. Densities of these rocks probably range from 2.6 g/cm³ for the quartzite to 2.9 g/cm³ for sillimanite schist.

Cenozoic rocks lap unconformably over the pre–Cenozoic rocks along the coast and fill the Los Angeles basin (33°58'N, 118°20'W) and smaller basins between the ranges. Over 2000

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density measurements have been made of core samples of the Los Angeles Basin (McCulloh, 1960) and these densities range from 2.1 g/cm³ for saturated Holocene alluvium to 2.6 g/cm³ for lower Cenozoic sand and shale at depths greater than about 3 km.

The Peninsular Ranges are divided into three structural blocks by the Elsinore and San Jacinto faults. The San Jacinto fault is the more active of the two, having historic breaks near Hemet and west of the Salton Sea caused by five earthquakes of magnitude 6.0 to 6.8 between 1915 and 1954 (Hileman and others, 1973, figure 4). No historic movement has been discovered along the Elsinore fault, but a number of small earthquakes with magnitudes less than 4 occurred along it in 1949 and 1970–1972 (Hileman and others, 1973, figures 22 and 54).

The San Jacinto fault is primarily a young strike–slip fault with a cumulative right–lateral movement of about 25 km since Miocene time (Sharp, 1967). The Elsinore fault is more of an enigma. Because of its arrangement parallel to the San Jacinto and San Andreas faults, one would suspect that it also would be dominantly a strike–slip right–lateral fault. However, the most detailed study of the fault indicates that the motion has been chiefly dip–slip in the vicinity of Temecula, the east side having moved down about 1 km (Mann, 1955). Other studies did not reach conclusions on the horizontal sense of movement but cited geologic evidence for limiting either right– or left–lateral strike-slip displacements to "small" (Sharp, 1968, p. 292) or "on the order of a few miles" (Morton and Gray, 1971, p. 73). New evidence from biotite isochrons show a prejudice for small right–lateral displacement, but the data control is inadequate to resolve the question (Krummenacher and others, 1975, figure 1).

Earthquakes have also occurred along the Newport–Inglewood fault zone (Hileman and others, 1973), which is largely concealed by the Holocene alluvium of the Los Angeles Basin. About 1 ½ km of right–lateral motion is inferred to have occurred along the fault since early Pliocene time (Yerkes and others, 1965, p. A48).

Regional Gravity

Bouguer anomalies are about –20 mgal along the coast between San Juan Capistrano and San Diego and gradually decrease eastward, reaching a low of about –90 mgal along an axis that parallels the coast but not the major faults. Farther east, gravity rises toward the Salton Trough, reaching values as high as –25 mgal near the eastern edge of the province west of Brawley. This east–west profile is complicated by a northward decrease in regional gravity, causing the –80 to –90 mgal contours to open in successively wider parabolic forms. Gravity is relatively flat over the San Jacinto Mountains but decreases gradually northward from about –75 mgal west of Palm Desert to –95 mgal at Mount San Jacinto.

These regional gravity variations bear a striking resemblance to the average elevation contours (figure 4). The average elevation along the coast is 150 m, which corresponds to the –15 mgal gravity contour (see Introduction and sections on the Great Basin and Transverse Ranges). Similarly, the average elevation at Mount San Jacinto is 900 m yielding a computed gravity contour of (–0.1) (900) or –90 mgal, which is only 5 mgal greater than the observed value there. Mount San Jacinto is located about 10 km east of the maximum average elevation of about 1000 m at that latitude, and the gravity behaves accordingly, although the data are sparse in that area (see index to gravity coverage and Oliver and others, 1980).

A local lack of correlation between regional gravity and average elevation indicates areas underlain by rocks in the upper crust with densities different from about 2.7 g/cm³. Aside from the basin areas, to be discussed in the next section, the major area of departure from normal gravity–elevation relations is in the western part of the southern California batholith. This area extends from the coast inland for about 50 km and is marked by a nearly benchlike gravity expression with a level of –20 ± 10 mgal, despite the average elevation increase to 600 m and the values of –60 mgal that would therefore be predicted for this distance from the coast. This area is underlain by old, mafic batholithic rocks which have mantle–type initial Sr^{87}/Sr^{86} ratios of 0.704. The rocks are quartz diorite with a probable average density of about 2.8 g/cm³. The gravity bench is also coincident with the area within the batholith containing numerous gabbroic bodies discussed above. Thus, the southern California batholith can be divided on the basis of the associated gravity field into two parts: an abnormally dense western half and a normal eastern half. The division between the two halves—the eastern edge of the gravity bench—is marked by the increased gradient, which reaches a maximum value of 10 mgal/km along the –55 mgal contour between Campo (lat 32°36'N, long 116°28'W), near the Mexican border, and the Winchester–Homeland area about 10 km west of Hemet (lat 33°45'N, long 116°58'W). The westward divergence of the –20 to –30 mgal contours to the west of the main gradient along the Elsinore fault zone is a separate problem discussed below and does not obscure the fact that the major gravity gradient crosses the Elsinore fault and is primarily related to the batholith.

Shawn Biehler (in Elders and others, 1972, figure 3) has modeled the crustal structure of the Peninsular Ranges along an approximately east–west profile through San Diego, using a density contrast of 0.35 g/cm³ between the crust and upper mantle. The model is controlled by offshore seismic data and shows an eastward crustal thickening from about 29 km under San Diego to about 32 km under the highest part of the Peninsular Ranges. Farther east, the model shows the crust thinning rapidly to 21 km at the center of the Salton Trough.

Local Basement Anomalies

Two types of basement rocks in this area are associated with gravity highs. One is the Catalina Schist, a glaucophanitic schist which crops out in the Palos Verdes Hills near Point Fermin (lat 33°44 N, long 118°18'W) about 20 km west of Long Beach (see McCulloh, 1957, for a detailed gravity and geologic map of this area); the other is gabbro, which makes up a number of bodies up to 10 km in size throughout the western half of the batholith. The 5– to 10–mgal residual gravity highs north of Fallbrook (lat 33°26'N, long 117°15'W), 4 km east of Lake Elsinore (lat 33°41'N, long 117°20'W), and 40 km east of the San Diego at Alpine (lat 32°52'N, long 116°45'W) are directly over gabbro bodies (Jennings and others, 1977).

The large horseshoe–shaped anomaly centered at Laguna Beach (lat 33°33'N, long 117°48'W) is harder to explain because no gabbro, glaucophane schist or other dense basement rocks crop out in the vicinity of the anomaly. However, Paleocene marine sedimentary rocks crop out at the north edge of the San

Joaquin Hills near the center of the anomaly (Jennings and others, 1977). Moreover, these hills are known from drilling to be the surface manifestation of a faulted anticline with 2 ½ km of structural relief (Vedder, 1975). The anticline and associated faults—the latter are shown on the base map—strike northwest roughly parallel to the coastline and the elongate axis of the closed 0-mgal contour. The northern part of the anomaly between East Irvine and Tustin is associated with another northwest-striking anticline (Yerkes and others, 1965, p. A49; J.G. Vedder, 1978, personal communication). Thus, the regional anomaly is at least partially the result of the superposition and coalescence of the gravity effects of two or more anticlines. The large size (about 25 mgal) and extent of the gravity high suggest that basement rocks were also involved in the San Joaquin Hills uplift. For example, a density contrast of about 0.4 g/cm^3 is required for a semi-infinite block 2 ½ km high and 6 km wide to cause a 25-mgal anomaly at a height of about 2 km above the block. A 0.4 g/cm^3 density contrast is larger than normally occurs between Paleocene and upper Tertiary rocks and usually indicates tectonic juxtaposition of pre-Cenozoic crystalline basement rocks with much lighter Cenozoic sedimentary deposits in California. The Laguna Beach gravity high is similar in amplitude and extent to the gravity high west of Long Beach and does not resemble the smaller gravity highs over gabbro in the Peninsular Ranges.

Basin Anomalies

The largest and deepest basin in the Peninsular Ranges is the Los Angeles Basin, which is both a physiographic alluviated lowland and a structural depression covering the area of Los Angeles and its suburbs (Yerkes and others, 1965). A simple Bouguer anomaly map with a contour interval of 1 mgal is available for the northwestern part of the basin (McCulloh, 1957). Complete Bouguer and regional gravity maps with an interval of 5 mgal are also available for the entire basin (McCulloh, 1960, figures 150.2 and 150.4). McCulloh's Figure 150.2 is nearly identical with the Los Angeles area of the State Map presented here except for details around the edges of the basin based on more recent data (Hanna and others, 1975b).

Bouguer gravity anomalies decrease from about +20 mgal on the coast west of Long Beach to a minimum closure of –80 mgal encircling the city of South Gate. North of the basin, Bouguer gravity rises to about –30 mgal in the Santa Monica Mountains, whereas on the northeast flank it reaches only about –60 mgal over crystalline rocks. A regional gradient of about 2 mgal/km, dipping northeast, is superimposed on the effect of the low-density sediments in the basin. The regional gravity gradient is consistent with the northeast increase in average elevation of about 450 m across the basin (figure 4). After removing regional gravity, the residual anomaly is about –75 mgal. McCulloh (1960) modeled the residual anomaly and showed that it is caused by a maximum thickness of about 10 km of Upper Cretaceous and Cenozoic sedimentary rocks.

Detailed gravity surveys have also been made in two small inland basins in support of hydrologic studies. One of these is Garner Valley (Durbin, 1975), which is not named as such on the State Map but is located under the closure of the –90 mgal contour 25 km south of the San Jacinto Mountains and just south of Lake Hemet at latitude 33°35′N, longitude 116°40′W. According to Durbin's one-mgal contour map, the gravity minimum is located on the San Jacinto fault zone and has a closure of about 5 mgal.

Another detailed gravity map of a Cenozoic basin is available for the gravity low at latitude 33°30′N, longitude 117°7′W just east of Temecula, which is 47 km east of San Clemente. The map is unpublished but available for inspection at the Geological Survey Water Resources Division office in San Clemente (Richard Moyles, oral communication, 1978).

Relation to Major Faults

The faults in the Peninsular Ranges have a more pronounced effect on gravity than in other parts of California. The types of effects include coincident gradients, associated lows, and pattern offsets.

The north end of the San Jacinto fault near San Bernardino has a coincident gravity gradient so steep that it is almost a step down to the northeast from about –75 to about –95 mgal. The line of maximum gradient is about 2 km southwest of the surface trace as shown on the base map, suggesting that the fault plane dips to the southwest in this area. Farther southeast, in the vicinity of Hemet, the Hot Springs fault splits off from the main San Jacinto fault zone, leaving a downfaulted valley that is filled with at least 2 km of sediment, judging from the amplitude of the gravity low over it. The gravity step into the valley is larger on the southwest side, indicating a larger vertical displacement there than along the Hot Springs fault.

South of Lake Hemet, there are several small gravity lows over the fault zone, but no convincing gravity evidence of right-lateral offset. The small 10 to 15 mgal highs on opposite sides of the Superstition Mountain fault are of similar aspect; if they were once continuous, their right-lateral offset would be about 16 km.

The gravity character of the Whittier-Elsinore fault system is somewhat different and is generally more supportive of dip-slip movements. There is a sharp gravity rise of 5 to 10 mgal across the Whittier fault, which indicates that denser rocks are nearer the surface on the northeast than they are on the southwest side of the fault. On the basis of seismic-reflection data, McCulloh (1960, figure 50.3) showed the Whittier fault as a high-angle reverse fault with a basement scarp on the north side about 0.6 km high buried by about 2 km of late Cenozoic sediments.

The north end of the Elsinore fault is marked by a sharp gravity low of about 15 mgal that probably indicates a buried narrow graben located on the fault line. The fault bedrock on both sides of a graben is exposed at Lake Elsinore, where it has been described by Mann (1955). The gravity low extends with varying amplitude as far south as Temecula, beyond which no significant areas of Cenozoic fill are associated with the Elsinore fault.

The gradient that divides the southern California batholith as described above crosses the Elsinore fault in the vicinity of Lake Henshaw without an obvious offset. South of the fault, the locus of maximum gradient, approximated by the –55 mgal contour, does bend toward the west and almost parallels the fault before turning more to the north right at the crossing. The bend to the west seems to curve around a group of gabbro bodies that displace the –30 to –45 mgal contours eastward near Cuyamaca Peak and may not be related to the fault. It is worth noting in this context that apparent left-lateral offset can be caused by vertical offset of a density discontinuity that dips to the east. In

any case, this throughgoing gradient seems to put a significant constraint on possible lateral movement of the Elsinore fault.

Gravity contours in the vicinity of Long Beach cross the Newport–Inglewood fault zone obliquely without disturbance. McCulloh (1960, figure 150.1) shows the section of the fault near Bellflower to be a reverse fault with about 0.3 km of upthrow on the northeast side of the fault. However, there are different types of basement on opposite sides of the fault, which suggests major strikeslip displacement (Warren Hamilton, written communication, 1978). For a density contrast of 0.3 g/cm³, the maximum gravity effect of a 0.3–km vertical displacement is about 4 mgal or less than one contour interval on the State map. Wiggles of about half a contour interval occur near the fault, but the effect is small.

The rise in gravity southwest of the Palos Verdes fault is much more pronounced. McCulloh (1957, section AB) has interpreted the gravity step there as indicating nearly 2 km of structural relief as the result of both anticlinal folding and thrusting of the Catalina Schist to the northeast over Miocene strata.

SALTON TROUGH

by Andrew Griscom[1]

Physiography and Geologic Setting

The Salton Trough is the northern structural extension of the Gulf of California and is topographically low, having an average regional elevation of less than 150 m in the southern part and valley floors at or below sea level. The east part of the trough southeast of the Salton Sea is termed the Imperial Valley, and at the opposite end of the Salton Sea the Coachella Valley extends 70 km to the northwest.

Three major right–lateral strike–slip faults extend along the trough and have a total strike–slip displacement perhaps as great as 300 km (Crowell, 1975). The San Andreas fault is located on the northeast side of the trough, and the southwest side of the trough is occupied successively by the Elsinore fault and the San Jacinto fault zone. The bordering ranges expose crystalline metamorphic and igneous rocks that within the trough are generally covered by great thicknesses of Cenozoic sedimentary deposits. The eastern half of the trough is an elongate structural depression occupying the Imperial Valley, Salton Sea, and Coachella Valley. Drill holes and geophysical data show that maximum depths to crystalline rocks exceed 4 km in the Coachella Valley and are over 6 km near Brawley south of the Salton Sea. West of this large structural depression, the trough is composed of smaller structural depressions separated by faults and occasional outcrops of uplifted crystalline rocks. At the south end of the Salton Sea five small rhyolite domes (Kelley and Soske, 1936; Muffler and White, 1969) intrude Pleistocene sediments. These domes contain abundant inclusions of basalt (Elders and others, 1972) and are associated with a more extensive magnetic anomaly (Griscom and Muffler, 1971) interpreted to be caused by an intrusion parallel to the trough and at least 30 km long, 5–8 km wide, and 2–4 km thick with its upper surface about 3 km below sea level. This intrusion may be mostly composed of basaltic rocks.

Associated with the rhyolite domes and the magnetic anomaly at the south end of the Salton Sea is the Salton Sea geothermal area (White and others, 1963; Muffler and White, 1969), where wells record the near–surface metamorphism of former sediments to greenschist–facies mineral assemblages of relatively high density.

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Regional Bouguer Gravity Field and Basin Anomalies

The Bouguer gravity anomalies of the Salton Trough have been studied by Kovach (Kovach and others, 1962) and in the greater detail by Biehler (Biehler and others, 1964; Biehler, 1964; Elders and others, 1972). Gravity values range from a closed low of –115 mgal in the Coachella Valley to –20 mgal near the Mexican border and at the south end of the Salton Sea. The northwest–trending gravity contours reflect the similar tectonic trends. A regional gravity high (Elders and others, 1972, figure 3) over the southern part of the Salton Trough (the Imperial Valley and the Salton Sea) trends northwest and ranges from a high of –30 mgal near the Mexican border to –60 mgal at the north end of the Salton Sea. The regional gravity high extends northwest of the Salton Sea, as is demonstrated by the highs flanking the more local intense gravity low associated with the Coachella Valley.

The gravity anomaly over the eastern structural depression in the Salton Trough varies from a low in the Coachella Valley to a high south of the Salton Sea. In the Coachella Valley, gravity analysis of the major gravity low suggested at least 4.7 km of sediments (Biehler, 1964). The asymmetry of the low shows that the sediment is thickest on the northeast side of the valley near the San Andreas fault. The steep gravity gradient across the San Andreas fault east of Indio (lat 33°45′N) is the result of a steep contact between crystalline rock and sediments that here exceed 4 km in thickness (Biehler, 1964). Southeast of the Coachella Valley, where the Salton Trough widens at the Salton Sea, the Bouguer anomalies rise to a local high of –20 mgal centered over the trough, and continue at a level of about –35 mgal southeast along the Imperial Valley to the Mexican border. These high values are unexpected because an east–west seismic–refraction profile across the valley at Westmorland, 8 km south of the Salton Sea, indicates that the interface between material having a longitudinal wave velocity of 4.7 km/s and basement having a velocity of 6.4 km/s is at most about 5.9 km deep (Biehler, 1964). Biehler also reported that in this same area the average density of sedimentary rocks from well samples to depths of 3 km is 2.40 g/cm³. Given a basement depth of only 3.5 km at the Westmorland profile, a residual gravity low of –40 mgal would be predicted assuming basement rock densities of about 2.67 g/cm³ (Biehler, 1964), but such a residual low is not evident on the gravity map. Biehler (1964) offered two explanations, both involving density decreases beneath the main structural trough, to account for the absence of the gravity low: (1) a thinning of the crust under the Salton Trough and (2) a local increase of crustal density beneath the trough. Biehler's thin–crust model shows that the gravity data require a crust only about 20–22 km thick, given a density contrast of 0.35 g/cm³ between the crust and mantle. The crust here is about 8–10 km thinner than in the adjacent areas of his model. Seismic–refraction data at the north end of the Gulf of California do not define the base of the crust, but it is "probably at a depth no less than 24 km below sea level" (Phillips, 1964). This result is comparable to Biehler's calculation. A denser crust under the Salton Sea and Imperial Valley is suggested by the large inferred basalt intrusion beneath the sediments of the Salton Sea area. Such mafic intrusions may

indeed be expected if the Salton Trough, like the Gulf of California, is the result of tensional thinning and spreading between the North America and the Pacific plates (Hamilton, 1961; Elders and others, 1972).

The local Bouguer gravity high at the south end of the Salton Sea has a maximum contour of –20 mgal and is 10–15 mgal above the regional background level. This anomaly probably reflects mostly the local increase in density of the former sedimentary rocks due to their metamorphism in this active geothermal area, but the inferred mafic intrusion could also contribute to the high. The metamorphism is most likely caused by the concealed mafic intrusion. Other known geothermal areas in the Salton Trough, such as the one near Brawley (lat 33°00'N, long 115°30'W), also coincide with local gravity highs 2–22 mgal in amplitude (Elders and others, 1972).

Southwest of the main structural trough of the Salton Sea and Imperial Valley, the various closed gravity lows and gravity highs are respectively the expression of structural depressions filled with low-density sediments and of structural elevations where high-density crystalline bedrock is commonly exposed.

Offset on the San Andreas Fault

On the northeast side of the Salton Sea northwest of the San Andreas fault is a gravity high with a maximum contour of –35 mgal. This anomaly is associated with the Orocopia Schist, one of a series of similar outcrops, the cores of crudely domical structures, forming a disconnected northwest-trending belt of schist in southern California and southwesternmost Arizona (Haxel and Dillon, 1978). Overlying the schist in thrust contact is a distinctive series of plutonic rocks which include Precambrian gneiss, norite, anorthosite, and syenite plus Triassic granodiorite and quartz diorite (Crowell, 1962; summarized in Hamilton, 1978). These distinctive rock assemblages together with the schist and their mutual thrust contacts have been used to demonstrate approximately 300 km of offset on the San Andreas fault since Miocene time by correlation of the Orocopia Schist with the similar Pelona Schist and associated rocks of the Sierra Pelona (lat 34°30'N, long 118°15'W) on the west side of the San Andreas fault in the Transverse Ranges (Crowell, 1962, 1975).

A local gravity high is associated with the Pelona Schist of the Sierra Pelona and is similar to the high over the Orocopia Schist in the Salton Trough. The source of the gravity highs is not obvious and is probably not the rocks exposed at the surface. The protoliths of the schist were predominantly quartzose graywacke with subordinate amounts of chert, basalt, thin limestone beds, and small pods and lenses of ultramafic rocks. Most are now metamorphosed to the greenschist or epidote-amphibolite facies and therefore are unlikely to have an average density in excess of about 2.72 g/cm^3. The surrounding and superimposed plutonic assemblages may well be denser than the schist; hence these structures, cored by schist, would not be expected to display a gravity high. The unknown basement rocks beneath the schist are considered most probably oceanic crust on the basis of the associated metabasalt and ultramafic rocks (Haxel and Dillon, 1978). Perhaps the gravity highs indicate relatively uplifted oceanic crust beneath the exposures of the schist. A second large area of Pelona Schist is in the eastern San Gabriel Mountains (lat 34°20' N, long 117°40'W); it does not display a gravity high and has not been directly correlated with the Orocopia Schist to determine offset on the San Andreas fault because of the absence of distinctive associated Precambrian anorthosite and syenite.

A strong gravity high with a maximum contour of –80 mgal and a local amplitude of about 30 mgal is located about 30 km northwest of the Coachella Valley (lat 34°05'N, long 116°55'W). The source of this anomaly is associated with an outcrop of mylonitized gneiss (Dibblee, 1964) that lies halfway between two small exposures of Pelona Schist, 15 km apart, each overlain by mylonitized gneiss (Dibblee, 1964; Rogers, 1969). The Pelona Schist probably also underlies the central area of mylonitized gneiss, which suggests that this gravity high is probably associated with Pelona Schist. As mentioned by Oliver in the section on the Transverse Ranges, this inferred belt of Pelona Schist and the associated gravity high both straddle the south branch of the San Andreas fault and preclude major offset here. Although there is no associated anorthosite and syenite, the gravity high suggests that this belt of rocks may correlate directly with the Orocopia Schist (and its gravity high) and thus may represent displacement of about 90 km within the fault zone as suggested by Crowell (1962, p. 39).

MOJAVE DESERT

by R.H. Chapman[1]

The Mojave Desert Province in California is a large wedge-shaped tectonic block bordered on the north and northwest by the Garlock fault zone and on the southwest by the San Andreas fault zone and the Salton Trough. Gravity values in the province range from above –25 mgal in some of the mountain ranges in the southeastern part of the area to below –145 mgal in Invanpah Valley (lat 35°25'N, long 115°20'W) in the northeastern part of the area.

Gravity values decrease both to the east and west of a regional gravity high that extends from the southeastern part of the area across the province to near Death Valley. This high follows the topographic low (figure 4) containing a 600 m closed depression. Hunt and Mabey (1966, p. A78) in their discussion of the Death Valley area suggested that the regional high may reflect a thinning of the earth's crust. The negative anomaly in the western part of the province may be a southern extension of the minimum which to the north has been attributed largely to an isostatic effect related to the Sierra Nevada (Oliver and Mabey, 1963).

Gibbs and Roller (1966) reported a crustal thickness of about 27 km at Ludlow (lat 34°44'N, long 116°09'W), near the central part of the province, based on seismic-refraction measurements. In apparent agreement with the gravity data, crustal thickness increases to the north in Nevada and decreases to the south toward the Salton Trough, where a crustal thickness of about 21 km was reported. Elders and others (1972) have estimated a crustal thickness of about 21 km in the Salton Trough using gravity data. A seismic-refraction profile from Santa Monica Bay to Lake Mead reported by Roller and Healy (1963), however, indicates that the base of the crust across nearly the entire northern part of the province is at a depth of about 26 km and is essentially flat, which is in apparent disagreement with the interpretation based on gravity data.

Local gravity anomalies in the Mojave Desert are not generally characterized by any one principal orientation (Mabey,

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1960). The relatively random pattern of the anomalies in much of the area distinguishes this province from the surrounding areas. Anomalies near the Garlock fault tend to parallel it (Mabey, 1960). Similarly, on the southwest, anomalies tend to parallel the San Andreas fault and the Salton Trough. In the northeast part of the area, anomalies tend to have north and northwest trends similar to those in the Great Basin Province to the north.

Many positive anomalies tend to follow the mountain ranges, and negative anomalies follow the intervening basins. Some of the strong positive anomalies are related to Precambrian igneous and metamorphic rocks that have average densities of at least 2.7 g/cm^3 (Healey, 1973; Mabey, 1960) in a series of mountain ranges just west of the Colorado River from the Dead Mountains (lat 35°00'N, long 114°45'W) on the north to the Big Maria Mountains (lat 33°50'N, long 114°40'W) on the south. Other positive anomalies evidently reflect Mesozoic mafic intrusive rocks that may range in density from 2.8 to 3.0 g/cm^3 (Chapman and Rietman, 1978).

Areas of Mesozoic granitic rocks are commonly characterized by anomalies that range from near zero to slightly positive (up to 10 mgal), in agreement with the range of measured density values for these rocks (between 2.60 g/cm^3 and 2.70 g/cm^3) (Nilsen and Chapman, 1974; Mabey, 1960), which is close to the value used for reduction of the gravity data. Some broad negative anomalies, however, such as those centered in Superior Valley near Goldstone Lake (lat 35°25'W, long 115°37'W), with amplitudes of at least 30 mgal, suggest the presence of batholiths of granitic rocks that are, on the whole, less dense than the surrounding rocks (Nilsen and Chapman, 1974; Healey, 1973). Assuming a density contrast of –0.10 g/cm^3 with the surrounding rocks, a mass at least 8 km thick is required to account for the Goldstone Lake anomaly (Nilsen and Chapman, 1974).

Negative anomalies are associated with Cenozoic sedimentary deposits including alluvium and lake beds, and with some areas of Tertiary volcanic rocks. Because of the pronounced density differences between Cenozoic sedimentary rocks and most of the older rocks (an average difference of perhaps about 0.4 g/cm^3), the gravity data are particularly useful in the Mojave Desert for indicating the thicknesses of the younger rocks in the valleys. A number of deep basins or troughs are suggested in the Mojave Desert area; for example, a northwest–trending negative anomaly with an amplitude of about 35 mgal, located north and northwest of Blythe (lat 33°40'N, long 114°40'W), indicates a basin more than 2 km deep (Peterson and others, 1967; Rotstein and others, 1976). Also in the far northwest corner of the Mojave Desert, in Antelope Valley (lat 34°50'W, long 118°30'W) and south of Rosamond Lake (lat 34°45'N, long 118°05'W), anomalies with amplitudes of more than 25 mgal each indicate other major basins (Mabey, 1960). These data have been used in exploration for borate deposits in the western Mojave Desert (Mabey, 1960) and for evaluation of water resources in some areas such as the Picacho–Bard basin in the southeast part of the area, southwest of the Chocolate Mountains (lat 32°50'N, long 114°35'W) (Mattick and others, 1973). In contrast to the areas with major negative anomalies, the lack of a significant anomaly in a valley area, such as between the Providence Mountains (lat 34°55'N, long 115°35'W) and the Clipper Mountains (lat 34°50'N, long 115°25'W), suggests that bedrock is near the surface.

Faults, particularly those that bound some of the mountain ranges, are commonly indicated either by relatively steep gravity gradients or by negative anomalies. For example, the southwest side of the Sacramento Mountains and the Saw Tooth Range (lat 34°35'N, long 114°40'W) (Chapman and Rietman, 1978), the southwest side of the Big Maria Mountains, and the west side of the Palen Mountains (lat 33°45'N, long 115°10'W) (Rotstein and others, 1976), both the northwest and southeast sides of Cantil Valley (lat 35°20'N, long 117°50'W) (Mabey, 1960; Nilsen and Chapman, 1974), and near Needles (lat 34°10'N, long 114°36'W) (Peterson, 1969; Chapman and Rietman, 1978) show steep gradients that are almost certainly related to faults. Three strong east–trending negative anomalies located in the south–central part of the Mojave Desert evidently represent major fault zones: the Pinto Mountain fault zone (lat 34°10'N, long 116°15'W), the Blue Cut fault zone (lat 33°55'N, long 115°45'W) and the Orocopia lineament (lat 33°40'N, long 115°45'W) (Biehler, 1964; Rotstein and others, 1976).

Some other major gravity features in the Mojave Desert area include: (1) a northeast–trending negative anomaly associated with Cantil Valley, (2) a relatively sharp, deep gravity low in southwestern Lanfair Valley (lat 35°05'N, long 115°15'W), (3) a north– to northwest–trending positive anomaly near Emerson Lake (lat 34°30'N, long 116°25'W), and (4) an east–trending positive anomaly near Barstow (lat 34°55'N, long 117°00'W).

The negative anomaly associated with Cantil Valley has an amplitude of at least 30 mgal. Mabey (1960) has estimated that Cenozoic deposits beneath the anomaly are more than 3.2 km thick in a tectonically depressed block between the Garlock and El Paso faults on the north and the Cantil Valley fault on the south.

The relatively sharp gravity low in southwestern Lanfair Valley, near Hackberry Mountain, is situated over Tertiary intrusive and extrusive rocks. The magnitude (more than 20 mgal) and subcircular form of this anomaly suggest that it is situated over a caldera-like structure from which the local volcanic rocks were erupted (Healey, 1973).

The positive anomaly with an amplitude of about 20 mgal near Emerson Lake is located between the Calico fault on the northeast and the Taylor Valley fault on the southwest. Because part of the area is characterized by numerous exposures of relatively dense Mesozoic mafic intrusive rocks (Rogers, 1969), the anomaly may indicate the presence of a relatively large mass of these rocks. The Barstow positive anomaly with an amplitude of about 15 mgal is also associated, at least in part, with a number of exposures of mafic rocks.

OFFSHORE CENTRAL AND NORTHERN CALIFORNIA

by E.A. Silver[1]

Free–air gravity anomalies over the continental margin off northern and central California result from the combined effects of ridges, basins, canyons, large faults, and the crustal thinning at the edge of the continent. South of the Mendocino escarpment major structural ridges reflected in the gravity field are Farallon Ridge, Santa Cruz high, and Santa Lucia bank. Major basins include the Bodega, Outer Santa Cruz, Sur, and Santa Maria basins. The Point Arena Basin does not produce a significant gravity effect.

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Of the ridges, Farallon Ridge is the longest and shows the largest gravity effect. The maximum free–air anomaly over the ridge is 50 mgal, 35 km west of Point Reyes. The anomaly dwindles rapidly to the north but continues with reduced amplitude to the west of Point Arena. South of the 50 mgal maximum the anomaly bends southeastward and trends toward Pigeon Point. Forty kilometers northwest of Pigeon Point a pronounced saddle in the anomaly field may correspond to a buried erosional notch or fault. Pioneer submarine canyon heads just seaward of this saddle. The basement rocks underlying the Farallon Ridge are granitic. Quartz diorite is exposed on the Farallon Islands and was dredged from Cordell Bank north of the islands (Hanna, 1952). Hoskins and Griffiths (1971) inferred its presence just offshore from Pigeon Point, but direct recovery of granitic rock there has not been reported. It is not known whether these rocks continue as part of the Farallon Ridge as far north as Point Arena, but the decreased gravity effect over this northern segment implies either an increase in depth to the top of these rocks or a decrese in density (and presumably in type) of the underlying rocks.

A gravity high of 30 mgal overlies the northwest end of the Santa Cruz structural high, but most of this structural high is characterized by an anomaly of less than 20 mgal. The anomaly, and presumably therefore the ridge, does not extend to the coast. Volcanic rocks have been sampled from the southwest side of this ridge, and Miocene and younger sediments cover the ridge (Hoskins and Griffiths, 1971). However, little is known of the geology of this feature.

Seismic–reflection profiles show several kilometers of late Miocene and younger strata on the east side of both the Santa Cruz high and Farallon Ridge, but strata are upturned only against the latter (Silver and others, 1971). This difference in structure suggests recent uplift only of the Farallon Ridge and may partly explain the stronger gravity effect of that feature.

The gravity lows of as much as –70 to –80 mgal along the lower continental slope between latitudes 37°40′ and 39°20′N and between latitudes 34°20′ and 36°00′N result from the effects of increasing water depth down the continental slope, the rapidly decreasing crustal thickness westward beneath the continental margin, and possibly a thick mass of sedimentary rocks under the continental slope.

Bodega Basin lies just east of Farallon Ridge and is nearly enclosed by the 0–mgal contour. The basin is divided by a structural high of low relief off Point Reyes. Two small areas in the northern part and one in the southern part have values as low as –20 mgal. The basin overlies granitic basement and contains 2.5 to 3 km of sediment, most of which is late middle Miocene and younger (Hoskins and Griffiths, 1971). The eastern margin of the basin is bounded in the southern part by the San Andreas and Seal Cove faults and in the northern part by the Point Reyes fault. The 0–mgal anomaly near the coast trends subparallel to these faults and outlines the ridges and basins between latitudes 37° and 39°N.

The granitic rocks underlying the Farallon Ridge and Bodega Basin are part of the Salinian block, a long sliver of dominantly granitic basement in central California, bounded on the east by the San Andreas fault and on the west, at least from Monterey south, by the Sur–Nacimiento fault. The latter fault is probably offset across Monterey Bay in a right–lateral sense by the San Gregorio fault zone. The amount of offset of a variety of geologic features across this fault has been estimated at 115 km (Graham and Dickinson, 1978b). The Farallon Ridge is granitic, but granitic rocks have not been recovered from the Santa Cruz high; hence it is possible that the west margin of the Salinian block passes between these ridges and lies along the west side of the Farallon Ridge.

The gravity data apparently conflict with the interpretation of large lateral offset on the San Gregorio fault. The gravity high that overlies the Farallon Ridge intersects the coast at Pigeon Point and appears to continue onshore into the Santa Cruz Mountains over the Ben Lomond batholith. This continuity across the fault may be fortuitous. Many granitic masses occur in the Salinian block, and the San Gregorio fault cuts the block at a low angle, so the chance of such a juxtaposition is significant. Alternatively, the continuity of the anomaly may indicate very little horizontal offset along the fault. A saddle in the gravity high and deflection of the contours in a right–lateral sense occur where the fault crosses the gravity high, as expected from the presence of such a fault, but these effects do not require large offset. Ironically, large right–slip offset on the San Gregorio was suggestsed initially on the basis of the offshore gravity map and the onshore geology, matching the Farallon Ridge at Pigeon Point with granitic rocks just north of Point Sur (Silver, 1974). The geologic studies of Graham and Dickinson (1978a and b) support large right–slip offset, but the new gravity map presented here raises doubts about such an interpretation. I believe the continuity of the gravity anomaly is fortuitous and that the fault has undergone large Neogene right–slip. But a more vigorous study of regional geologic relations and an attempt to establish offset lines is clearly needed.

Outer Santa Cruz Basin is outlined partly by the 0–mgal contour. Its gravity effect is less than –10 mgal in the southeast where sediment thickness exceeds 1.5 km (Hoskins and Griffiths, 1971). Sediment thickness in the northern part of Bodega Basin, by comparison, is 3 km (Hoskins and Griffiths, 1971), and the gravity effect there is greater (more negative) than at Outer Santa Cruz Basin.

Free–air gravity highs with local closures of about 30 mgal are associated with both Guide and Pioneer seamounts, but the anomalies are displaced to the west of the seamounts by 7 km and 4 km, respectively. Magnetic data obtained at the same time as the gravity survey (National Oceanic and Atmospheric Administration, 1974a) show magnetic highs of 500 to 600 gammas offset to the west of both seamounts by comparable distances when compared with detailed bathymetry (National Oceanic and Atmospheric Administration, 1974b). These offsets may be partially due to navigation errors, but the character and location of the gravity and magnetic anomalies suggest that they are not simply reflections of the seamounts but caused by dense magnetic plate–like masses that extend southwestward from the seamounts below the ocean floor.

Free–air gravity over Monterey Bay and the continental slope west of the bay is dominated by the topographic effect of Monterey Canyon. Free–air anomalies as low as –90 mgal are found along the canyon axis and thus obscure possible structural effects of deeper origin. The west–trending free–air gravity high west of Point Sur also is largely topographic, separating gravity lows over Monterey Canyon to the north and the Sur Basin to the south.

The Sur Basin has a free–air gravity low of –70 mgal. Although maximum sediment thickness (3 km on the east side of the basin) is no greater than in the Bodega Basin, water depth below the anomaly minimum is 1 km, compared to less than 100 m in Bodega basin. The steep gradient along the east side of the Sur Basin marks the location and trend of a large fault with a vertical basement relief of over 3 km. This fault probably connects with the San Gregorio fault to the north and the Hosgri fault to the south (Silver, 1978; Graham and Dickinson, 1978a; 1978b).

Santa Maria Basin, in contrast to the Sur, Bodega, and Outer Santa Cruz basins, shows an irregular set of local lows and highs, the lows reaching –30 to –40 mgal. This pattern reflects the very irregular underlying structure. The basin is bounded on the east by the Hosgri fault and on the west by the Santa Lucia Bank fault, which shows a gravity effect and is nearly on the –10mgal contour approximately between latitudes 34°40′ and 35°10′N. Nearshore gravity data are insufficient to evaluate the effect of the Hosgri fault. Four of the five gravity lows mapped over the basin lie near the Santa Lucia Bank fault, indicating greater sediment thickness adjacent to the fault than in the central part of the basin; the one exception is a centrally disposed gravity low at latitude 35°10′N. Seismic–reflection profiles show complex basement structure beneath this basin.

Free–air gravity anomalies differ in trend on either side of the Santa Lucia Bank fault. To the west, a broad gravity high trends slightly west of north, parallel to the bank and to the fault. To the east, anomalies over the Santa Maria Basin trend northeast. West of the bank, a northwest–trending gravity high follows the top of the Santa Lucia escarpment, reaching +20 mgal over a topographic high. The gravity high plunges to the northwest. Olivine basalt was recovered by dredging the continental slope at the north end of this gravity high, and Cretaceous sandstone was dredged near the top of Santa Lucia Bank, just below the topographic high marked by the closed +20 mgal contour. Between this outer gravity high and that overlying Santa Lucia Bank is a gravity low, also lessening northwestward, that overlies a sedimentary basin—as seen in reflection profiles—containing nearly 1 km of sediments.

Northwest of Santa Lucia bank a free–air gravity high reaching –10 mgal bounds the gravity low over Sur Basin on the west. This gravity high overlies a structural ridge that does not appear to be separated from the adjacent basin by a fault, as is the case to the south. Rounded boulders of quartz monzonite were dredged from the southern part of this structural ridge, at about latitude 35°30′N. The gravity high over this ridge terminates on the north at Sur Canyon, just south of a west–trending anomaly off Point Sur. Elongate free–air gravity highs on the lower part of the continental slope between latitudes 35°30′ and 37°30′N are associated with Davidson, Guide, Pioneer and Mulberry seamounts.

The gravity field between Point Arena and the Mendocino fault is very flat, and free–air anomalies closely record the topographic effect of Viscaino and Noyo submarine canyons. The lower slope negative anomaly is not well developed in this region, reflecting the very gentle bathymetric slope from the coastline to the deep seafloor and possibly a lower than normal rate of change of crustal thickness as well.

The geology and gravity field of the continental margin changes abruptly at the Mendocino fault. A west–trending gravity high reaching +30 mgal over the Mendocino Ridge marks both high topography and dense basaltic rocks there. Based on gravity modeling, Talwani and others (1959) suggest thicker crust south of the fault but lower density mantle to the north. This interpretation is consistent with the presence of younger oceanic crust (< 7 m.y.) north of the fault and older crust (25–30 m.y.) to the south (Atwater, 1970).

The oceanic lithosphere north of the fault is undergoing subduction beneath the continental margin (Silver, 1969, 1971). The slope–base gravity low is a function not only of surface slope and increasing depth to mantle eastward but also of thick sediments ponded in a buried trench at the base of the slope and deformed on the lower part of the slope (Silver, 1971). The gravity low at the head of Trinidad Seavalley exceeds –60 mgal and coincides with a thick section of upper Cenozoic sediments trapped in a basin behind an upper slope structural ridge (Silver, 1971). The ridge is associated with a long gravity high that extends, parallel to the gravity low over the basin, into the margin offshore of southern Oregon. The slope–base low just north of the Mendocino fault exceeds –80 mgal and may be a combined effect of the gravity low over the lower part of the continental slope and the north side of the Mendocino escarpment, or it may indicate thicker sediments in this corner of the subducting plate.

COAST RANGES

by R.H. Chapman[1] and Andrew Griscom[2]

Physiography and Geologic Setting

The Coast Ranges Province is composed of northwest–trending ranges and intervening valleys, reaching maximum elevations of about 2700 m near latitude 40°N but rarely exceeding 2000 m. The maximum average elevation (figure 4) is about 1100 m at latitude 40°N.

Two major faults, the San Andreas fault and the Nacimiento fault zone, strike northwest through the province and subdivide it into three major areas of distinctive basement rocks. East of the San Andreas fault and west of the Nacimiento fault zone, the basement is composed of the Franciscan assemblage, a mass of melange and imbricated rocks that are predominantly graywacke, siltstone, and shale, subordinate volcanic rocks and chert, and minor amounts of serpentinite and mafic intrusive rocks (Bailey and others, 1964; Hamilton, 1978). These rocks range in age from late Jurassic to Eocene. The assemblage resulted from the accumulation of materials scarped off the oceanic crust during eastward subduction beneath California. Between the San Andreas fault and the Nacimiento fault zone is the Salinian terrane, where basement is composed of granitic and metamorphic rocks. Overlying these various basement materials are Cretaceous and Tertiary sedimentary deposits as well as lesser amounts of Tertiary and Quaternary volcanic rocks. Cenozoic volcanic rocks are especially abundant north of San Francisco as far as Clear Lake (lat 39°N), where several young volcancoes are shown on the map. The Cenozoic sedimentary basins are generally elongated northwest, may be deeper than 3000 m (Smith, 1964), and are bounded locally by steep–dipping faults.

Bouguer Anomalies North of Latitude 39°N

North of latitude 39°N the Bouguer gravity anomalies over the Coast Ranges Province are characterized by a smooth gradient

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sloping from values of +20 mgal near the shore to a closed low of −115 mgal centered at Shell Mountain near latitude 40°N. The closed low also corresponds in location with a generalized topographic high of 1050 m (figure 4) so that the gravity anomaly in part can be regarded as the isostatic effect of a root of low–density crustal rocks (Griscom, 1973a; Chapman and others, 1975). The gradient is produced by a combination of three effects: (1) the transition from thin high–density oceanic crust to thick low–density continental crust, (2) the transition from high –density oceanic mantle to low–density continental mantle, and (3) thickening of the total section of the Franciscan assemblage to a maximum of perhaps 10 km (Griscom, 1973a, figure 1) in the vicnity of the closed low.

Gravity levels over the Coast Ranges Province increase southward from the closed minimum of −115 mgal at latitude 40°N to about 0 mgal near San Francisco. This change reflects the change in crustal thickness from about 33 km at the gravity minimum (Griscom, 1973a, figure 1) to 22–25 km at San Francisco (Eaton, 1966) and also perhaps an increase in upper mantle density at San Francisco. Stewart (1968) from seismic–refraction data placed the base of the Franciscan at a depth of 10–16 km in the Diablo Range 60 km east of the San Francisco Peninsula, and placed the base of the crust at about 30–32 km. These dimensions are similar to the crustal model calculated from gravity and seismic–refraction data at latitude 40°N (Griscom, 1973a). Simila (1978) reported apparent upper mantle P–wave velocities of 7.5–7.7 km/s in the northern Coast Ranges as compared to the value of 8.18 km/s obtained by Stewart (1968) for the Diablo Range east of San Francisco. The velocity differences, if not an azimuthal effect (Peselnick and others, 1977), support the conclusion from gravity data that upper mantle densities are greater in the San Francisco area than in the northern Coast Ranges.

The smoothness of the gravity field over the Coast Ranges north of latitude 39°N contrasts strongly with the irregularity of the gravity field east of the Coast Range thrust and the inferred deep structure of this province. The sedimentary rocks of the Franciscan were deposited in a deep oceanic environment upon oceanic crust, the mafic rocks of which should show a density contrast of perhaps 0.3 g/cm^3 with the Franciscan sedimentary rocks. Thus the smoothness of the gravity field indicates that the bottom surface of the Franciscan is smooth on a regional scale, probably with no local relief in excess of 1.5 km. This deduced smoothness contrasts strongly with the intricate structure of the Franciscan rocks themselves and leads to the inference (Griscom, 1973a, 1973b) of a relatively smooth surface of décollement at or a short distance above the bottom of the Franciscan in this area. This décollement surface is to be expected if the Franciscan assemblage is composed of materials scraped off an oceanic plate against the inner wall of a trench during subduction. Calculations from the steep gravity gradient at Point Delgada (lat 40°N) indicate a maximum dip of about 20° northeast for the formerly active décollement surface (Griscom, 1973a, figure 1). North of the Mendocino fault zone (lat 40° 20′N) the subduction beneath the continental margin is still active (Silver, 1971), and here the dip on the décollement surface is probably less than 10°, judging by the gravity gradient in the vicinity of the −50 mgal contour.

The northward motion of the Mendocino triple junction (the junction of the Mendocino fault zone, the San Andreas fault, and the subduction fault) along the coast of California has progressively terminated subduction beneath the Franciscan south of the Mendocino fault zone (Atwater, 1970). Cenozoic tectonism increases southward within the Franciscan south of the fault zone, perhaps due to the temporal and physical adjustments to cessation of subduction. The increasing complexity south of latitude 39°N of the gravity field associated with the Coast Ranges Province may be indirectly a result of a northward migration of the triple junction and hence a result of the southward increase of the time span since local subduction ceased. To the south, increased normal faulting and volcanism produce local concentrations of low–density material and associated local gravity features.

Two major local gravity features are observed within the broader regional pattern north of latitude 39°N. The first is a gravity low at the mouth of the Eel River (lat 40°35′N) superimposed on the regional gradient. This low is caused by the low density Tertiary sedimentary rocks (Ogle, 1953) of the Eel River Basin. The northeast side of the basin is bounded by the Little Salmon and Yaeger faults, which show as a steep linear gravity gradient. A second gravity feature is the irregularly linear gravity high on the east side of the Coast Ranges Province in the general vicinity of the Coast Range thrust and extending as far north as the east side of the closed −115 mgal low, for a total length of about 125 km. The high has an ampliltude of 10–25 mgal. Directly east of the thrust is the ophiolite sequence (Bailey and others, 1970) of serpentinized ultramafic and mafic rocks that forms the oceanic crust upon which the Great Valley sequence was deposited. These rocks, where now predominantly serpentinite, are not expected to display significant gravity expression because of the lack of density contrast with the Franciscan. Nevertheless, five local closures or near–closures are found in the gravity contours along this high, all of which can be ascribed to high–density rocks in the ophiolite above the Coast Range thrust (Chapman and others, 1975). From south to north these local features include: (1) a −40 mgal closure at latitude 39°N; (2) a −50 mgal closure 20 km to the north; (3) a nearly closed nose in the −45 mgal contour about 10 km northwest of the previous feature; (4) a −45 mgal closure 10 km farther northwest over a local thrust sheet of Great Valley volcanic rocks (Brown, 1964) in an outlier of the Coast Range thrust; and (5) a −75 mgal closure at latitude 40°N. Regardless of these local features, the crest of the linear gravity anomaly is commonly at or west of the Coast Range thrust, which from geologic and aeromagnetic data (Griscom, 1973a) is known to dip steeply east. Thus the bulk of the high cannot reflect the ophiolite. Griscom (1973a) suggests two explanations for the anomaly. Directly below the Coast Range thrust, the Franciscan assemblage is metamorphosed to higher density rocks of blueschist facies (Blake and others, 1967). The blueschists can cause the anomaly with a density contrast of only 0.1 g/cm^3. Alternatively, aeromagnetic evidence (Griscom, 1966) indicates that a mass of magnetic material, the crest of a gently folded thick magnetic sheet of rock, possibly serpentinitized ultramafic rocks, occurs at a depth of 1.5 to 3 km below the surface along the axis of the gravity high. This concealed mass may also be a source for the gravity high.

Various small negative closures or flexures within the area from latitude 39°N to latitude 40°N with amplitudes of about −5 mgal are associated with intermontane basins containing alluvial fill (Chapman and others, 1975). Some of the anomalies are larger in areal extent than the valleys, suggesting that not only the fill but also structural displacements of the layers in the upper crust affect the anomalies.

South of Latitude 39°N

Bouguer anomalies in the Coast Ranges Province decrease southeastward from approximately −10 mgal in the area just north of San Francisco to about −25 mgal near the latitude of Monterey (36°35′N) and to −50 mgal or less east of Point Conception (lat 34°30′N). The decrease in anomaly magnitude corresponds in a general way to a decrease in the proportion of exposed Franciscan and granitic rocks relative to exposures of Tertiary and Quaternary sedimentary rocks, at least south of Monterey. Also, the average elevation of the Coast Ranges decreases to the southeast (figure 4). Nevertheless, seismic–refraction data indicate a crustal thickness of 22 to 25 km at San Francisco and about the same thickness at Camp Roberts (lat 35°48′N, long 120°44′W), about 260 km to the southeast (Eaton, 1966, figure 3). From Camp Roberts southward, however, crustal thickness may increase as suggested by the gravity data because seismic data indicate a thickness of about 35 km near Los Angeles, south of the Transverse Range Province (Healy, 1963).

The general level of the Bouguer gravity field decreases inland in the Coast Ranges south of latitude 39°N. The smooth regional gradient noted north of latitude 39°N is partially obscured in the southern area by local anomalies related to the complex geologic features in this area. Most of these local anomalies trend northwest or north parallel to numerous faults and the regional geologic structure.

Much of the coastline from about San Luis Obispo (lat 35°20′N) to about Fort Bragg (lat 39° 27′N) is marked by linear positive anomalies approximately parallel to the coastline. These positive anomalies are mostly related to exposures of granitic, mafic, and metamorphic rocks in the Salinian terrane west of the San Andreas fault and to exposures of Franciscan rocks south of Monterey and west of the Nacimiento fault zone. Although these positive anomalies primarily reflect the relatively dense rocks along the coast, they are accentuated by a combination of the regional gravity gradient and the presence on the continental shelf of gravity lows related to basins of Tertiary sedimentary rocks. Examples of coastal gravity highs a few tens of milligals in amplitude include those related to exposed granitic rocks from Point Reyes (lat 38°00′N) to Bodega Head (lat 38°20′N) north of San Francisco; Montara Mountain (lat 37°32′N) and Ben Lomond Mountain (lat 37°05′N) south of San Francisco; the granitic and metamorphic rocks exposed in the San Lucia Range south of Monterey Bay (lat 36°20′N), and Franciscan assemblage rocks along the coast from about latitude 36°N to near San Luis Obispo.

Other positive anomalies southwest of the San Andreas fault are related to granitic rocks northwest of Paso Robles (lat 35°40′N, long 120°45′W), and east of Santa Margarita (lat 35°25′N, long 120°35′W) and Franciscan assemblage rocks near Stanley Mountain (lat 35°05′N, long 120°13′W).

Near Stewart's Point (lat 38°39′N) north of Point Reyes, a sharp positive anomaly apparently is associated with outcrops of basalt that may represent the floor of Gualala Basin (Silver and others, 1971; Chapman and Bishop, 1974). The aeromagnetic map of this area (U.S. Geological Survey, 1976) suggests that this basalt may extend westward offshore for at least 10 km.

The coastal gravity highs are separated by negative anomalies in a few areas where sedimentary basins cross the coastline at, for example, the Santa Cruz (La Honda) Basin (lat 37°22′N) 35 km south of San Francisco (Chapman and Bishop, 1968b), at the offshore Salinas basin (lat 36°45′N), at a thick section of Tertiary sedimentary rocks south of Estero Bay (lat 35°20′N) (Burch and others, 1971), and at the Santa Maria basin (lat 34°57′N) in the southern part of the Coast Ranges (Rietman and Beyer, 1980).

The northwest–trending positive anomaly associated with Ben Lomond Mountain appears to be a shoreward continuation of the offshore Farallon Ridge–Pigeon Point anomaly. Northeast of the Farallon Ridge–Pigeon Point anomaly trend, negative anomalies also suggest continuity in the offshore area between the Bodega and Santa Cruz basins. Similarly, on the southeast, negative anomalies associated with the Outer Santa Cruz and the Salinas basins are in approximate alignment. According to Graham and Dickinson (1978), however, the San Gregorio fault, which crosses these anomalies, has an estimated 115 km of offset in a right lateral sense in the Monterey Bay area. If this figure for offset is approximately correct, the apparent alignment of gravity anomalies must be fortuitous. This is discussed in more detail by Silver (this report).

The northeast boundary of the Coast Ranges is characterized in many places by steep gravity gradients; these gradients probably represent the contact between Franciscan rocks or rocks of the Great Valley sequence and lower density Tertiary and Quaternary rocks in the Sacramento and San Joaquin Valleys. The linear steep gradients along the northeast side of the Coast Ranges are interrupted in a few places such as east of Clear Lake (lat 39°00′N, long 122°30′W), Suisun Bay (lat 38°08′N, long 122°03′W), and south of Panoche Valley (lat 36°30′N, long 120°47′W), where negative anomalies represent synclines or other structures superimposed on the margin of the Great Valley. Strong positive anomalies are associated with some areas of Franciscan rocks that are close to the overlying Coast Range thrust along the east side of the Coast Ranges, such as in the Diablo Range north of Panoche Valley (lat 36°43′N), between Cholame and Parkfield (lat 35°50′N) (Hanna and others, 1972), west of Lake Berryessa (lat 38°32′N), and near Vallejo (lat 38°08′N). These anomalies might reflect metamorphic Franciscan rocks, possibly in combination with ultramafic and mafic rocks in some places, as postulated for the positive anomalies west of the ophiolite sequence north of latitude 39°N.

Many of the major faults in the Coast Ranges are marked by relatively steep gravity gradients, but only in those areas where the faults bound rock units that are characterized by distinct density differences. For example, the San Andreas fault north of San Francisco forms the boundary between granitic rocks of the Salinian block on the southwest and rocks of the Franciscan assemblage on the northeast (Clement, 1965; Chapman and Bishop, 1968b). Because the average densities of granitic and Franciscan rocks are similar, there is no density contrast, and no apparent gravity anomaly. The lack of a gravity anomaly also suggests that deeper layers of contrasting density are not significantly offset in the vertical direction at the fault. Farther south along the San Andreas fault (near lat 36°40′N), however, the fault forms the boundary between granitic rocks in the Gabilan Range on the southwest and lower density Tertiary sedimentary rocks on the northeast. In this area, a steep gravity gradient marks the fault zone, separating a high over the granitic rocks from a low over the Tertiary sedimentary rocks (Pavoni, 1973; Bishop and Chapman, 1967). Byerly (1966), however, found that a Bouguer anomaly profile in this area corrected for near–surface geology shows no evident anomaly associated with the fault. This result is in apparent agreement with the lack of an anomaly for the San Andreas fault north of San Francisco noted above.

Southwest of the San Andreas fault, strong negative Bouguer gravity anomalies of a few tens of milligals amplitude are found in association with numerous irregularly spaced valleys and basins containing Tertiary and Quaternary sedimentary rocks from Point Arena on the north to the Santa Maria basin (lat 34°40′N, long 120°05′W) and Cuyama Valley (lat 34°55′N, long 119°37′W) on the south. These include the prominent long linear anomalies over Salinas Valley (centered near lat 36°25′N, long 121°20′W) and the Carrizo Plain (centered near lat 35°23′N, long 120°05′W).

Bouguer gravity values northeast of the San Andreas fault in the Coast Ranges are similarly generally high in areas of Franciscan rocks and low in areas of Tertiary and Quaternary sedimentary rocks. Locally strong lows include those associated with the Santa Clara Valley near San Jose (lat 37°23′N, long 121°52′W), a linear anomaly extending southeastward from Hollister (lat 36°50′N, long 121°25′W) along the San Andreas fault, and an anomaly trend east of the Hayward fault that includes closures at Livermore Valley (lat 37°40′N, long 121°53′W) and San Pablo Bay (lat 38°08′N, long 122°20′W). Distinct highs are related to the Diablo Range (lat 37°35′N, long 121°40′W) and, in general, to the exposed Franciscan rocks north of San Francisco. A strong gravity high is located over the San Emigdio Mountains near the south end of the San Joaquin Valley (lat 34°53′N, long 119°12′W) (Hanna and others, 1975a). This anomaly is primarily the reflection of metamorphic and granitic rocks that are present in this area on both sides of the San Andreas fault.

Exposures of relatively dense "greenstone" show sharp local gravity highs of 5 to 10 mgal in many areas in Franciscan terrane. Large masses of ultramafic rocks may be characterized by either local highs or lows, depending in part on the relative proportion of serpentinite and unaltered ultramafic rocks present. Lows are found over ultramafic rocks near Cuesta Pass, north of San Luis Obispo (lat 35°23′N, long 120°38′W) (Burch and others, 1971), Joaquin Ridge (lat 36°38′N, long 120°35′W) (Byerly, 1966; Bishop and Chapman, 1967), and The Cedars (lat 38°38′N, long 123°08′W) (Thompson and Robinson, 1975; Chapman and Bishop, 1974). Small highs are associated with Burro Mountain (lat 35°52′N, long 121°16′W) (Burch and others, 1971), east of Cape San Martin, and possibly with the Point Sal ophiolite (lat 34°54′N, long 120°37′W).

Noteworthy Bouguer gravity anomalies in the Coast Ranges include a 40–mgal high over Mount Diablo (lat 37°55′N, long 121°57′W). The gravity interpretation by Wood (1964) supported a piercement structure hypothesis for the origin of this strong anomaly where diabase was forcefully emplaced. However, an analysis by Andrew Griscom (unpublished data, 1978) of the Mount Diablo magnetic anomaly (Griscom, 1966) indicates that an antiformal folded tabular mass of mafic rocks fits the data at least as well as does a deep–rooted piercement structure.

Of particular interest also are the Bouguer gravity lows related to (1) the east side of the north end of Santa Clara Valley near San Jose (Evergreen low), (2) Livermore Valley, and (3) the Clear Lake area. Analysis of the Evergreen gravity low suggests that a graben extends into the lower crust and possibly into the upper mantle (Robbins, 1971), as there is no density contrast at the surface adequate to explain this anomaly. According to the interpretation by Robbins and others (1977), gravity data at Livermore Valley suggest not only a great thickness of Cretaceous and Tertiary rocks but also a thinner crust north of the valley than to the south in the Diablo Range. The negative anomaly with an amplitude of more than 25 mgal south of Clear Lake in the vicinity of the Clear Lake volcanic field has been interpreted as a possible magma body at a depth of 10 km or less (Chapman, 1975, 1978b; Isherwood, 1976). This anomaly is associated with Pleistocene and Holocene volcanic rocks, the Geysers steam field, numerous hot springs, and a region of high heat flow (Urban and others, 1976).

GREAT VALLEY

by H.W. Oliver[1] and Andrew Griscom[1]

General Geology

The Great Valley of California is about 700 km long and 100 km wide, and ranges in elevation from about 10 m in the west–central area to about 150 m at the north and south ends (figure 5). Elevations averaged to a distance of about 40 km are somewhat greater and reach about 300 m around the periphery of the valley, except where it opens westward toward San Francisco Bay (figure 4). The south half of the Great Valley is called the San Joaquin Valley and drains to the north, except the south end, parts of which have closed drainage; the north half is the Sacramento Valley and drains southward.

The Great Valley is a very large asymmetric syncline with 5 to 10 km of uppermost Jurassic to Quaternary sedimentary deposits along the structural axis defined by the configuration of older basement rocks (Kilkenny, 1951; Ingersoll, 1978). This axis is located near the western edge of the valley about 20 km west of the present axis of deposition marked by the Sacramento and San Joaquin Rivers. Drilling and seismic data indicate that the eastward shift in the axis of deposition has been progressive and began with the uplift of the west side at the end of the Cretaceous (Safonov, 1962). The most severe period of deformation was in the middle Pleistocene, when extensive folding and faulting affected the upturned west valley sedimentary strata (Hackel, 1966). Some of these faults–for example, the Quaternary faults in the Elk Hills west of Bakersfield and the Midland fault zone west of Sacramento–are shown on the base map.

The major structure along the strike of the valley is a tilting of all the pre–Pleistocene beds to the south and an accompanying southward thickening of late Cenozoic formations (Safonov, 1962). This general pattern is interrupted by arching of the pre–Cretaceous basement rocks near Stockton and Bakersfield (Repenning, 1960, figure 2).

Densities

The density of the surficial alluvial deposits is known from gravity measurements over local topography to average about 1.9 g/cm^3. Density and sonic logs in deep wells indicate that densities of older sediments increase approximately linearly with depth to about 2.6 g/cm^3 at a depth of about 5 km (Byerly, 1966; R.O. Hovey, personal communication, 1970).

The densities of the pre–Cretaceous basement rocks beneath the valley sediments are not well known. Density measurements of 41 basement cores in the vicinity of Madera (Bayoumi, 1961, appendix 1) ranged from 2.43 g/cm^3 for serpentinite to 3.11 g/cm^3 for mafic meta–igneous rocks. Petrographic studies of

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basement cores suggest that the same general range of basement rock types and corresponding densities occurs within the Great Valley basement as in the Sierra Nevada (May and Hewitt, 1948; Thompson and Talwani, 1964).

Gravity Anomalies

Bouguer gravity anomalies range from about +25 mgal over Sutter Buttes to –110 mgal west of Red Bluff. The closure of the –110 mgal contour in this area is the northernmost of a series of gravity lows that extends south along the west side of the Great Valley all the way to the White Wolf fault south of Bakersfield. This feature is referred to here as the west side gravity low.

A series of gravity highs extends both north and south from the closure over Sutter Buttes at least as far north as Red Bluff and as far south as Fresno. Several gravity highs farther north form an elbow that strikes into crystalline rocks northwest of Redding, and are thought to be caused by older rocks of the Klamath Mountains Province. South of Fresno the gravity ridge is interrupted by a broad negative closure of the –45 mgal contour, and continuity of the anomaly is uncertain. One possibility is that it diminishes greatly in amplitude and continues to the west of the negative closure near Raisin City, being manifest as south–pointing flexures in the –45 to –60 mgal gravity contours south of Stratford over the Tulare Lake Bed. Farther south, an extension of the gravity anomaly connects it with the gravity high centered about 15 km northwest of Bakersfield, although this connection is obscure west of Delano. The 700–km–long axis of the gravity high is thus broadly arcuate, being slightly convex to the west–southwest. Ivanhoe (1957, figure 2) suggested another possible extension of the major gravity high south of Fresno by bending the axis to the east of the –45 mgal negative closure, passing through the saddle near Easton, and connecting with the highs near Delano and Bakersfield. A third possibility is that the series of highs does not extend south of Fresno. Whatever the case, the distinctive anomaly north of Fresno will be referred to as the Great Valley gravity high in this report.

Another nearly linear gravity high occurs along the east side of the San Joaquin Valley between Clovis and Porterville. The amplitude of the anomaly near Dinuba, 50 km southeast of Fresno, is about 25 mgal. The gravity high was referred to as the Dinuba gravity lineament by Oliver and Robbins (1980).

Other Bouguer gravity highs include the East Valley gravity anomaly (Cady, 1975, figure 4) about 30 km southeast of Sacramento, the anomaly near Hanford (lat 36°23′N, long 119°37′W), and the circular high at Sutter Buttes. Strong gravity lows occur at Rocklin (30 km northeast of Sacramento) and north of Madera. The double low near Madera was termed the Madera doublet by Ahmed (1965).

The West Side Gravity Low

The connected Bouguer gravity lows along the west side of the Great Valley occur over the thickest part of the section of Cretaceous and Cenozoic sediments, which here ranges in thickness from 6 to 11 km. Although the minimum Bouguer anomalies are similar in both the north and south parts of the Valley—closure of –110 mgal at Red Bluff, and a southern closure of –100 mgal south of Bakersfield—the relative magnitude of the anomalies as compared with values in the adjacent Coast Ranges varies widely (15–20 mgal at Red Bluff, 50–60 mgal south of Bakersfield). The anomaly south of Bakersfield delineates the southern basin which is filled with an estimated 10 km of Cenozoic sediments (Repenning, 1960, figure 2). The residual anomaly is significantly larger in this area than near Red Bluff in the Sacramento Valley, where great thicknesses of sediments are also known to occur, because sediments at the south end of the San Joaquin Valley are mostly unconsolidated late Tertiary deposits that have a larger density contrast with the Franciscan rocks in the Coast Ranges than the Sacramento Valley sediments, which are mostly more–indurated Cretaceous deposits. The deepest well in the Great Valley is located in the southern basin 30 km south of Bakersfield and bottoms in Miocene sedimentary rocks at a depth of 6.9 km (Munger Oilogram, 1977).

The closure of the gravity low over the southern basin nearly pinches out near Fellows where the Bakersfield arch has brought basement rocks within about 3 km of the surface (Repenning, 1960). North of McKittrick, the valley sediments thicken to about 7 km within the closure of the –85 mgal contour and include low–density diatomaceous sediments beneath local closures west of Lost Hills (Barton, 1948).

In general, the deeper parts of the Great Valley fill coincide with negative closures 70 km west of Fresno, 50 km west of Merced, and at Rio Vista, the last anomaly overlying 11 km of sediments (Safonov, 1962, figure 5). The axis of the west side gravity low does not directly overlie the synclinal basement axis but coincides with the average axis as integrated over the multitude of horizons and associated density contrasts between the numerous Cretaceous and Cenozoic formations. The late Cenozoic formations have the most easterly axis, the lowest densities, and the largest influence on the integrated effect (Byerly, 1966).

The Great Valley and Dinuba Gravity Highs

The source of the Great Valley gravity high has been the subject of speculation since Woollard (1943, plate 3) first traversed it about 25 km north of Bakersfield as part of his transcontinental gravity and magnetic profile of North America. With some insight from other areas, Woollard proposed that the source of the anomaly was a buried gabbro body, although he had no idea of the dimensions from the single profile. About 10 years later, Ivanhoe (1957) released a small–scale gravity map of the Great Valley with a contour interval of 20 mgal based on Standard Oil of California data that showed the great extent of the gravity high. Ivanhoe did not have magnetic coverage of the Valley at that time and interpreted the gravity feature as an "isostatic hinge line," that is, a relative maximum separating the effects of a great thickness of low–density sediments on the west side of the valley and a low–density mountain root beneath the Sierra Nevada (see next section). Although Ivanhoe's reasoning had some validity, the gravity high was later found to have a substantial magnetic anomaly associated with it at least as far south as Fresno (Grantz and Zietz, 1960; Meuschke and others, 1966; Zietz and Kirby, 1968; Cady, 1975). South of Fresno, the only non–proprietary magnetic data across the valley consist of a few high–level aeromagnetic traverses, which show that the magnetic anomaly continues down the center of the valley but with significantly diminished amplitude and increased breadth. Depth estimates of the magnetic high indicate that the dense magnetic mass causing both the gravity and magnetic anomalies crops out on the buried basement surface as far south as Fresno and perhaps plunges below the basement surface in the southern San Joaquin Valley (Griscom, 1966). The breadth of the gravity anomaly near Tulare Lake Bed is about 18 km and is suitable for

a source at the top of the basement, which is buried about 4 ½ km in this area (Smith, 1964).

As the Great Valley gravity and magnetic highs terminate short of basement outcrops at both the north and south ends of the Great Valley, it is of interest to look for similar anomalies that extend into basement rocks. The Dinuba gravity lineament along the east side of the San Joaquin Valley, noted above, is similar in both amplitude and direction, and would look more like the Great Valley gravity high were it similarly buried by 2 to 4 km of sediments (Oliver and Hanna, 1970). The Dinuba feature is associated with mafic and ultramafic rocks that crop out at Smith Mountain near Dinuba 5 km north of Dinuba at latitude 36°35′N, longitude 119°22′W) and in the Sierra Nevada south of Porterville (Oliver and Robbins, 1980). These rocks have been dated and determined to be remnants of late Paleozoic (30 m.y.) oceanic crust that have been sutured to older continental rocks of the Sierra Nevada (Saleeby, 1975, 1977). The densest, most magnetic rocks along the suture are olivine gabbro of Early Cretaceous age, which was regarded by Saleeby (1975, p. vii) to have been "preferentially emplaced into the structurally weakened zones provided by the disrupted ophiolite belt."

The source of the Great Valley gravity and magnetic anomalies is also generally considered to be a tectonically emplaced fragment of oceanic crust (Griscom, 1973; Cady, 1975; Jones and others, 1976). In one computer model of the anomalies near Sacramento, the average density of the fragment is 2.98 g/cm^3 and the average magnetization is 3.8×10^{-3} emu/cm^3, properties that are reasonable for a gabbroic lower crustal layer (Cady, 1975, figure 7). The form of the anomalous body is like a gable with a more gently dipping western slope, and the body extends to a computed depth of about 10 km below the basement surface. The age of the interpreted oceanic crustal fragment is unknown, but it is presumably the same as or between the ages of the Coast Range ophiolite (151–160 m.y.) and the ophiolites in the Sierra foothills (250 to 300 m.y.) (Irwin, 1978, figure 2).

Semi–Local Anomalies

Both the elongate gravity high southeast of Sacramento and the gravity high at Hanford have associated magnetic highs of several thousand gammas, and they are also thought to reflect buried gabbroic rocks cropping out at the buried basement surface (Griscom, 1966; Cady, 1975; R.M. Hovey, personal communication, 1970). The small gravity high located 5 km southeast of Dinuba has been explored by magnetic, seismic, and drilling methods and found to be associated with gabbro as well as related basement topography (Born, 1956).

The highest gravity value in the Great Valley, more than +25 mgal, is within a circular gravity high centered over the Sutter Buttes, an eroded Pliocene volcano (Garrison, 1962) in the Sacramento Valley. This circular high is also centered on the axis of the Great Valley gravity high, perhaps by coincidence, and its approximate residual amplitude is +25 mgal as determined from a north–south profile taken along the axis of the linear high. The circular anomaly is the result of two effects: (1) the relatively higher density of the intrusions of porphyritic andesite and rhyolite and (2) the updoming of the surrounding older and more dense sedimentary rocks from which large volumes of gas have been obtained.

The gravity lows on the east side of the valley at Rocklin (lat 39°47′N, long 121°10′W) and near Madera (lat 37°4′N, long 120°02′W) indicate low–density granitic rocks within the basement (Cady, 1975; Ahmed, 1965; Robbins and others, 1977). The Madera doublet represents a 40–km westward salient of the Sierra Nevada batholith, most of the salient being buried under valley fill. The northernmost of the two lows of the gravity doublet has been drilled and the basement core found to be garnet–bearing leucocratic trondhjemite (sodic granite) with an average density of 2.67 g/cm^3 (F.C. Dodge, written communication, 1972).

Relation to Faults

Historic movement has occurred along the White Wolf fault at the south end of the Great Valley, the Kern Front fault north of Bakersfield, the Cleveland Hill fault near Oroville (lat 39°27′N, long 121°25′W), and a fault on the west side of the valley near Antioch (lat 38°1′N, long 121°48′W). The significance of the decrease in Bouguer gravity anomalies to the northwest across the White Wolf fault near Bear Mountain is discussed in the next section. In the Great Valley, the White Wolf fault cuts across the southern basin at approximately the –85 mgal contour and causes sharp bends in the –90 to –95 mgal contours near Mettler. The correlation with these contours terminates short of the intersection with the Pleito fault to the west, suggesting that the two faults are not continuous. The Pleito fault cuts across gravity contours farther west but is reflected by the sharp gravity gradient at its east end near Grapevine.

The Kern Front fault is an active normal fault, the west side moving down relative to the east side (Manning, 1973). The fault plane dips about 70°, and the blocks are creeping relative to each other at the average rate of 1.1 cm/year, according to releveling data. The stratigraphic throw of upper Miocene beds is about 60 m. The eastward decrease in gravity in this area is generally considered to parallel an eastward decrease in the density of basement rocks (Hanna and others, 1975a), so it is not surprising that the southern segment of the fault having historic movement cuts across the gravity contours. The northern, shorter segment, just east of Famoso, is parallel to and near the maximum gravity gradient, suggesting that movement there may be related to basement lithologic contrasts. Farther north along the east side of the valley, mapping of the concealed faults of pre–Quaternary age between Porterville and Clovis (13 km northwest of Fresno) is based largely on vertical offsets in the water table. The fault at Clovis seems to be related to the north end of the Dinuba gravity lineament, and detailed gravity studies of that section of the fault are in progress (Braun, Skaggs, Kevorkian and Simons, Inc., Fresno, CA, written communication, 1978).

The historic fault, marked "1975," about 15 km southeast of Oroville is known as the Cleveland Hill fault and is the surface rupture that occurred at the time of the 5.7–magnitude earthquake of August 1, 1975 (Hart and Rapp, 1975; Clark and others, 1976). The fault is a normal fault dipping 60° to the west, and the west side moved down 0.36 m relative to the east side at the time of the earthquake (Savage and others, 1977). According to aftershock data, the extent of rupture along the strike of the fault was 7.5 km, and no movement occurred along the fault just west of Lake Oroville to the north or along the "shear zone" to the south (Lahr and others, 1976). There is no obvious relation between the 1975 rupture and regional gravity contours, which are associated primarily with known lithologic contrasts within the basement rocks (see next section). The 1975 surface rupture is on a sharp bend in the –40 to –65 mgal Bouguer

anomaly contours and at the southern edge of an east–west gradient that extends to the northern edge of Lake Oroville. The rupture is also on the east limb of a gravity high that trends N30°W through Oroville and that appears to be an extension of the shear zone. The regional anomalies to the east are clearly associated with the Bald Rock batholith and the Smartville ophiolite (see next section), but the rupture area and the area farther west are covered with Holocene alluvium, and the sources of the anomalies in that area are presently unknown.

The concealed northeast–trending fault through Red Bluff is of some geophysical interest because its existence was interpreted from magnetic data (Griscom, 1973, figure 2) independently of its later inclusion on this fault map base by Jennings (1975). According to C.W. Jennings (oral communication, 1978), the fault shown on the base map is known as the Red Bluff fault within private industry and has been mapped by seismic methods. According to the interpretation of seismic data, the block to the northwest of the fault has moved up relative to the southern block, but the direction of strike–slip movement, if any, is unknown. The Great Valley gravity high, discussed above, together with the associated magnetic anomaly, appears to be cut off by the Red Bluff fault; so strike–slip offset may have occurred. The gravity ridge that strikes northwest between Byrnes Creek and Redding is probably not an extension of the Great Valley high because it extends into the Trinity ultramafic sheet north of Redding, and this sheet is much older than the likely age of the source of the Great Valley gravity high (Griscom, 1973). Zircon ages of the Trinity sheet are in the range 440–480 m.y. whereas the plausible age of the source of the main Great Valley anomaly is within the range 160 to 300 m.y. (Irwin, 1978, figure 2).

The major concealed Midland fault about 40 km southwest of Sacramento has been studied by subsurface methods in connection with exploration of the Rio Vista gas field. The gas is primarily west of the fault within the thick section of Cenozoic sediments marked by the closure of the –55 mgal gravity contour. The vertical offset along the Midland fault zone is down to the west and ranges from zero for Pliocene strata to ½ km for Eocene strata and about 1 km for pre–Cretaceous crystalline rocks (Safonov, 1962, figure 5). An average density contrast across the fault of 0.1 g/cm^3 with an average offset of ½ km would produce a gravity step of 6 mgal. This gravity effect is on the order of the observed westward decrease in gravity across the fault near Rio Vista. The local wiggle in the –45 mgal contour west of the Midland fault near Brentwood reflects the anticlinal structure of the gas field.

Perhaps the second most important fault in the Great Valley after the White Wolf fault is the Stockton fault, which cuts across the Great Valley between Tracy and Stockton to a point near Peters. The Stockton fault consists of a zone of three parallel reverse faults with a total throw of about 1 km upward on the south side (Hoffman, 1972); these three faults form the Stockton arch, which separates the San Joaquin structural basin from the Sacramento basin to the north (Safonov, 1968). The Stockton arch is reflected in the gravity contours as an interruption in the west side low at Tracy and as an offshoot of the Great Valley gravity high to the southwest of Stockton that is not associated with any known magnetic feature (Robbins and others, 1977, figure 2).

SIERRA NEVADA

by H.W. Oliver[1]

Physiography, General Geology, and Densities

The Sierra Nevada is a competent fault block that has been tilted up to the east during late Cenozoic time (Bateman and Wahrhaftig, 1966). The mountains culminate in a nearly continuous crest along the east side of the range. On the base map the range is marked by long and short green dashes because it coincides with county boundaries over most of its length. The Sierra crest includes most of the highest peaks, such as Mount Whitney (4756 m, 14,496 ft) just west of Lone Pine and North Palisade Peak (4673 m, 14,242 ft) about 30 km southwest of Bishop.

The fault block is made up chiefly of granitic rocks of the Sierra Nevada batholith, and they have an average density of 2.68 g/cm^3, very close to the Bouguer reduction density of 2.67 g/cm^3. The wallrocks on both sides of the batholith and roof pendants and septa within it consist of Paleozoic and Mesozoic metamorphic rocks having on the average slightly higher densities than the batholith (Oliver, 1977). The densest rocks are olivine–hornblende gabbros which range in density up to 3.2 g/cm^3; they are associated with, but not part of, an ophiolite belt in the western foothills (Saleeby, 1978). The least dense rocks having significant volume are pre–Cretaceous shale and slate, which crop out in the western Sierra foothills and average about 2.5 g/cm^3 (Oliver and Robbins, 1980, table 3). Proglacial deposits with densities of about 2.0 g/cm^3 occur in some of the west–draining valleys. In Yosemite Valley these deposits are as thick as 600 m according to the interpretation of seismic data (Gutenberg and others, 1956) and recent drilling by the National Park Service (G. Witucke, written communication, 1975).

The major faults within the Sierra Nevada as shown on the base map are the pre–Quaternary Kern Canyon, Melones, and Bear Mountain faults; but the latter two may not be faults in the classic sense but rather tectonic zones of polymict melange and presumably old sutures (Hamilton, 1978). Quaternary and historic movements have taken place along the Sierra Nevada fault zone, which bounds the province on the east, and along the White Wolf and Kern Front faults near Bakersfield.

The Gravity Field

Bouguer gravity anomalies decrease to the east across the western Sierra Nevada foothills from a high value of about –50 mgal at the east edge of the Great Valley to a regional gravity low whose axis is generally located just west of the Sierra crest. Bouguer anomalies along the gravity low vary, being about –130 mgal east of Bakersfield, decreasing to a minimum of about –240 mgal west of Mammoth (somewhat north of the highest topography), and rising gradually to about –190 mgal near Lake Tahoe. The gravity low passes to the east of the Sierra crest and back west again near Bishop and is modified by the negative effect of sediments in Owens Valley, Long Valley, and Mono basin (see section on the Great Basin). The axis of the gravity low is shown in Figure 4 relative to the generalized topography.

Superimposed on this east–dipping regional gradient are a series of elongate gravity highs over the western foothills with

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amplitudes of 10 to 30 mgal. Two major lows in the foothills reach Bouguer anomaly values of –95 mgal about 35 km northeast of Sacramento and –135 mgal about 40 km east of Chico.

Isostasy

The main source of the gravity low over the eastern Sierra Nevada is the Sierra Nevada root, which supports the excess mass of the mountain range in approximate isostatic balance (Byerly, 1938). According to interpretation of seismic data (Bateman and Eaton, 1967), the root consists of low–velocity low–density crustal material and thickens at the expense of higher velocity mantle rocks from a normal thickness of about 20 to 25 km along the western edge of the Sierra Nevada to about 55 km under the Sierra crest. Farther east, the crust thins gradually to about 30 km beneath the Great Basin.

There is some disagreement regarding the form and thickness of the seismically determined root (Carder and others, 1970; Carder, 1973), but the analysis of the gravity data shown on the map taken along Eaton's seismic profile through Bishop tends to confirm the major features of Bateman and Eaton's crustal model (Oliver, 1977, figure 4). More recent gravity analysis along an east–west profile through Mount Whitney (Oliver and Robbins, 1980) suggests that there may be two separate mountain roots under the Sierra Nevada: one beneath the Sierra crest and the other beneath the Great Western Divide marked on the base map just west of the Kern Canyon faults. However, the computations show that the gravity effects of the two roots coalesce into a single gravity feature that is difficult to distinguish from the effect of a single root located midway between them.

The elevations averaged to a radius of 41 km (E_{41}, figure 4) correlate with Bouguer anomalies (BA) over normal crystalline rocks having densities near 2.67 g/cm^3. The approximate empirical relation is

$$\overline{BA} = a + b\,E_{41}$$

where both a and b vary somewhat, but are about –10 mgal and –80 mgal/km respectively for the Mount Whitney region (Oliver and Robbins, 1980). Thus the 1500–m contour (figure 4) approximately correlates with the –130 mgal contour (gravity map).

The reason for the correlation is that the form of the average elevation contours approximates the gravity effect of the Sierra Nevada root (see Introduction). I have tested this hypothesis against calculations of the gravity effect of both the seismically determined root and 12 different hypothetical models that assume perfect isostasy. The Airy–Heiskanen isostatic model with T = 20 km (Heiskanen, 1938) produces the best fit to observed Bouguer anomalies, but computations of this effect are presently limited to three profiles across the Sierra Nevada (Oliver, 1973, appendix 3).

Interpretation of Local Anomalies

Although the axis of the regional gravity low closely follows the axis of maximum average elevation (figure 4), there are some local perturbations associated with rock masses of unusually low density. One such perturbation in the vicinity of Mount Whitney occurs where the axis of the gravity low is displaced to the east of the maximum average elevation by the negative effect of the Whitney pluton. This pluton is rich in potassium, has an unusually low average density of about 2.64 g/cm^3, and extends for a distance of 60 km along the Sierra crest (Moore and du Bray, 1978). After removal of regional gravity, the residual gravity anomaly is about –11 mgal (Oliver and Robbins, 1980).

A similar perturbation occurs west of Mount Dana, the second highest peak in Yosemite National Park (figure 4). Here the regional gravity low is displaced to the west of the maximum average elevation by the negative effect of the Cathedral Peak Granodiorite (Batemen and Chappell, in press; Oliver, 1977, figure 5).

The gravity lows northeast of Sacramento and east of Chico also are the result of low–density granitic plutons. These foothill plutons are surrounded by high–density metamorphic rocks instead of average–density granitic rocks, and the gravity effect is therefore more pronounced. The anomaly northeast of Sacramento lies directly over the Rocklin pluton (Strand and Koenig, 1965; Swanson; 1978), for which density measurements of selected samples are as low as 2.55 g/cm^3 (F.C. Dodge, written communication, 1977). The extension of the circular gravity low into the Great Valley suggests that the quartz diorite extends westward beneath the valley sediments. On the basis of magnetic data, Cady (1975, p. 16) believed that the granitic rocks crop out on the buried basement surface as far west as the –70 mgal contour and that its contact with metamorphic rock dips west.

The strong gravity low east of Chico is nearly coincident with the Bald Rock batholith studied by Compton (1955). The closure is over 30 mgal, indicating a minimum thickness of 8 km for the batholith if there is a density contrast of –0.1 g/cm^3 with the surrounding metamorphic rocks. Compton (1955, p. 44) wondered whether or not the Bald Rock batholith and several adjacent plutons are "merely large cupolas of an extensive elongate pluton that underlies the northwest Sierra." The gravity map indicates that this is not the case, but that the main thickness of granitic rocks lies directly under the Bald Rock batholith.

The positives anomalies along the west edge of the Sierra Nevada occur primarily over mafic and ultramafic rocks, the greenstone belt of Thompson and Talwani (1964),now recognized as ophiolitic sequences of late Paleozoic through middle Mesozoic oceanic crustal rocks (Cady, 1975; Saleeby, 1977, 1978). The large gravity high about 40 km east of Marysville, culminating in a closed –15 mgal contour, lies directly over the Smartville ophiolite complex of gabbro, sheeted diabase, and pillowed metabasalt with some pyroclastic andesite (Bond and others, 1977). The gravity high 40 km east of Sacramento denoted by a "+" within the closed –25 mgal contour occurs over the Pine Hill Intrusive Complex of Springer (1974), which is composed largely of olivine gabbro and clinopyroxenite. Fifty samples of the gabbro have an average density of about 3.1 g/cm^3, a value which contrasts sufficiently with the surrounding metavolcanic rocks (2.7 to 2.9 g/cm^3 density) to account for the anomaly (Andrew Griscom, personal communication, 1978). Smaller positive anomalies, 10 to 20 mgal in amplitude, occur over probable ophiolites near Sonora (lat 37°58'N, long 120°21'W), Coulterville (lat 37°26'N, long 120°15'W), Dinuba (lat 36°33'N, long 119°24'W), and Porterville (lat 36°4'N, long 119°21'W). The 25–mgal anomaly near Dinuba has been modeled by Saleeby (1975, figure A1–3), who attributed it to a 9–km thickness of gabbro with an average density of 3.1 g/cm^3.

Residual gravity lows occur over low-density sediments along the shore of Lake Tahoe and in Sierra Valley (55 km N20°W of the north end of Lake Tahoe). The Lake Tahoe anomaly has a local amplitude of at least −15 mgal and is probably larger over the lake itself where no gravity data have been obtained. The Bouguer anomalies have been corrected for the effect of water in the lake, which is about 450 m deep; so the gravity low there is caused by sediments below the lake bottom that are known from seismic-reflection (air gun) data to extend to at least 400 m below the bottom or at least 850 m below lake level (Hyne and others, 1972). The minimum amplitude of the gravity anomaly (15 mgal) suggests that the sediments may be as much as 800 m thick (assuming $\Delta g = 0.5$ g/cm³). The better-determined Bouguer gravity field over Sierra Valley has a local depression of about −15 mgal relative to an ambient level of about −165 mgal. This gravity low has been interpreted by Jackson and others (1961) to represent a thickness of 750 to 900 m of Cenozoic deposits.

A residual gravity low of 9 mgal occurs over the section of low-density sediments in Yosemite Valley and causes the wiggles pointed downstream in the −160 mgal to −195 mgal Bouguer anomaly contours. Similar wiggles occur in the −195 mgal to −210 contours where they cross the South and Middle Forks of the Kings River. Both of these Kings River valleys have been glaciated, and these data suggest that they contain comparable thicknesses of stream and glacial deposits, perhaps as much as 600 m (Oliver and Robbins, 1980).

Relation of Gravity to Major Faults

The Sierra Nevada fault zone along the east margin of the southern Sierra is characterized by a steep gravity gradient that produces an eastward decrease in Bouguer anomalies of 10 to 20 mgal along the range front. In the vicinity of Lone Pine, the fault zone is split into two major segments, and the gravity decrease is much greater across the Owens Valley segment, along which historic movement has occurred. By contrast, there is almost no change in Bouguer anomalies across the Independence segment of the Sierra Nevada fault zone west of Lone Pine (see Pakiser and others, 1964, for a detailed interpretation of this area).

The Sierra Nevada fault zone north of Bishop consists of north-striking discontinuous segments arranged en echelon with an overall strike of about N30°W. These segments are not reflected significantly in the Bouguer anomalies, but some of the offsets are reflected, such as along the south side of Long Valley. Here, the maximum gravity gradient coincides approximately with the −245 mgal contour and a concealed fault (Pakiser and others, 1964; Kane and others, 1976).

The Kern Canyon fault strikes north and nearly bisects the southern part of the mountain range. It is a right lateral fault, subparallel to the Sierra Nevada fault, but it does not appear to offset an overlying 3.5 million-year-old basalt flow near latitude 36°15′N. The amount of right-lateral offset of the contacts of Late Cretaceous granitic bodies increases to the south from about 2 km at the north end of the inferred fault (shown with dashes on the map) to about 13 km at latitude 36°00′N (Moore and du Bray, 1978). The gravity field seems to be related to the fault in two ways: (1) a gravity low of 5 to 10 mgal is manifest as broad south-pointed wiggles in the −165 mgal to −185 mgal contours and (2) the −190 mgal contour appears to be offset in a right-lateral sense by about 8 km. The gravity low is not related to isostasy (Oliver and Robbins, 1980).

The White Wolf fault is not continuous with the Kern Canyon fault, and indeed the historic movement in 1952 was primarily left-lateral. However, in the vicinity of Bear Mountain the southeastern block has been thrust over the San Joaquin Valley sediments, and the fault exhibits a small component of right-lateral movement (Buwalda and St. Amand, 1955). The total amount of Cenozoic vertical offset at Bear Mountain is about 3 km, and this offset is reflected as a gravity step of 10 to 15 mgal (Hanna and others, 1975). The gravity step widens to the southwest as the basement scarp plunges to sediment depths of as much as 10 km due south of Bakersfield. Northeast of Bear Mountain, plutonic rocks have been thrust over other plutonic rocks, and the gravity step disappears because of the absence of a density contrast across the fault.

The Kern Gorge fault northeast of Bakersfield is related to a maximum gravity step of 7 mgal, up to the east, where the fault has brought Sierra granitic rocks into juxtaposition with Cenozoic sediments, but there is little or no gravity relief associated with faults within the southwestern Sierra foothills.

Serpentinite occurs from Mariposa (about 37 ½°N) nearly to Lake Almanor (about 40°N) within melanges associated with both the Melones and Bear Mountain fault zones (Jennings and others, 1977), and generally underlies intermittent gravity lows along the zones because the serpentinite is significantly lower in density ($\sim$2.5 g/cm³) than the surrounding granitic and metamorphic rocks (2.7–2.8 g/cm³). This effect produces local chevroning of the −65 and −70 mgal contours over the Melones fault southwest of Sonora (see Robbins and others, 1977). A gravity gradient is associated with the Melones fault between Baxter and Downieville (Oliver and others, 1974; Oliver and Robbins, 1974b) and is accounted for primarily by the contrast between dense Mesozoic metavolcanic rocks on the west of the fault (average density about 2.8 g/cm³) and lower density Paleozoic metasedimentary rocks to the east (average density about 2.6 g/cm³) (Jennings and others, 1977; Oliver, 1977). The eastward displacement of the maximum gravity gradient over the northward extension of the Bear Mountain fault in the vicinity of New Bullards Bar Reservoir (about 39½°N) indicates that the fault plane dips to the east.

GREAT BASIN

by H.W. Oliver[1]

Physiography and General Geology

The Great Basin sector in California is bounded on the south by the Garlock fault, on the west by the Sierra Nevada and Modoc Plateau, on the north by the Oregon border and on the east by the Nevada border (figure 5). The Great Basin is that part of the Basin and Range province having a closed drainage system, and it extends across Nevada into western Utah (Fenneman, 1946).

The province is characterized by north-trending mountain ranges separated by elongate basins as long as several hundred kilometers. The most prominent ranges are the Panamint Mountains (elevation 3.3 km; lat 36 ½°N), the White Mountains (elevation 4.4 km; lat 37½°N), and the Warner Mountains (elevation 3.1 km; lat 41½°N). The series of basins to the east of the Sierra Nevada are, from south to north: Owens Valley

[1] U.S. Geological Survey, Menlo Park, CA 94025.

(elevation 1.2 km), Long Valley (2.1 km), Mono Basin (2.0 km), Bridgeport Valley (2.1 km), and Honey Lake Valley (1.2 km). Panamint Valley (0.5 km) and Death Valley (–0.1 km) lie respectively west and east of the Panamint Range. Surprise Valley (1.5 km) is located east of the Warner Mountains. The greatest local relief in the California sector is between the Panamint Range and Death Valley (3.4 km). Saline Valley (0.3 km), located 40 km northeast of Owens Lake, has the greatest topographic closure (1.3 km).

Most of the ranges consist of Precambrian to Cretaceous crystalline rocks, Paleozoic sedimentary rocks, and Tertiary volcanic rocks. The valleys are filled with late Cenozoic nonmarine sedimentary deposits and extrusive igneous rocks. The Precambrian rocks crop out over a considerable area in the vicinity of Death Valley (Jennings and others, 1977), and they have a higher average density range (2.76 – 2.86 g/cm^3) than Mesozoic plutonic rocks (2.60 – 2.67 g/cm^3) (Chapman and others, 1973). The Cenozoic deposits are significantly lower in density, varying in density from 1.7 g/cm^3 for tuffaceous deposits in Mono Basin (L.C. Pakiser, written communication, 1975) to about 2.5 g/cm^3 for indurated middle Tertiary sedimentary and flow rocks (Nilsen and Chapman, 1974; Chapman and others, 1973).

The major structures in the Great Basin are normal faults bounding most of the ranges which are tilted as much as 30° (Stewart, 1978). The ranges east of the Sierra Nevada typically are tilted to the east whereas the Warner Mountains in northern California are tilted to the west. In addition to the major normal faults, which strike approximately north, strike-slip faults strike approximately northwest through some of the basins and have major right-lateral displacements. Examples of Quarternary northwest-trending strike-slip faults in eastern California include the Death Valley–Furnace Creek fault zone, the unnamed fault zone along the west side of Saline Valley, the Honey Lake fault, and the Likely fault. The strike of the Sierra Nevada fault zone is more northerly, but the trend of the zone of en echelon faults north of Bishop is northwest and nearly parallel to the Death Valley fault.

The structural development of the basin and range structures is generally considered to have begun in eastern California about 17 million years ago and to have been largely completed by 7 million years ago, although there has been continuing movement along many of the fault zones during Quaternary and even historic time (Stewart, 1978; Jennings, 1975). The 17 million year date marks the transition from predominantly compressive tectonics (related perhaps to a subduction zone) to extensional tectonics (related to wrench faulting, back-arc spreading, or some other factor) (Stewart, 1978). Estimates of the amount of extension in an east–west direction across the Great Basin in Nevada range from 10 to 100 percent, but most fall in the range 20 to 30 percent (Stewart, 1978). Wright and Troxel (1973) concluded that the extension in the Death Valley region was about 40 percent.

Regional Gravity

Bouguer gravity anomalies over the ranges generally vary inversely with the average topographic elevation (figure 4). Although a detailed study has not been made, the constant of proportionality for the Great Basin in California may have a higher value (about –100 mgal/km) than the constant determined for the Sierra Nevada (about –80 mgal/km) (see section on the Sierra Nevada, this report). That is, the regional Bouguer anomalies (BA) are related to average elevation averaged to a distance of 41 km by the approximate relation

$$BA \sim -100\ E_{41} \qquad (1)$$

where E_{41} in kilometers yields BA in milligals. The constant –100 mgal/km compares with a value of –105 mgal/km (0.032 mgal/ft) determined by Mabey (1966) from data in Nevada where elevations were averaged to a radius of 64 km.

The estimated constant –100 mgal/km is based on simple trial and error testing of the coefficients –85, –100, and –115 mgal/km along the California–Nevada border from the Garlock fault to the Warner Mountains (Table 5).

The largest positive residuals occur over Precambrian metamorphic rocks and Tertiary volcanic rocks whereas negative residuals occur over Mesozoic granitic rocks within the ranges.

The similarity between Bouguer anomalies and regional elevation (figure 4) is not obvious on the 5–mgal contour map because of the myriad of relative gravity lows over the basins. The relation is more apparent on gravity maps with 10–mgal contour intervals (Diment and others, 1961, figure 2; Oliver, 1977, figure 1), and obvious by comparing the 30–mgal interval map (figure 3) with Figure 4. The general eastward increase in gravity and decrease in elevation is illustrated in a section from the southern Sierra Nevada to Death Valley by Oliver and Mabey (1963, figure 1).

Table 5. Relation between average elevations, Bouguer anomalies, and type of basement rocks along California–Nevada border from the Garlock fault to the Oregon border.

North latitude	*Average elevation E_{41} (km) (Fig. 4)*	*$\Delta g \sim -100\ E_{41}$ (mgal)*	*Bouguer anomaly BA (mgal)*	*Residual gravity BA-Δg (mgal)*	*Exposed basement rock type*[1]
35½°	1.05	-105	-110	-5	Mesozoic granitic rocks
36½°	.90	- 90	- 81	+9	Precambrian metamorphic rocks
38°	2.10	-210	-220	-10	Mesozoic granitic rocks
40°	1.50	-150	-145	+15	Tertiary volcanic rocks
41½°	1.65	-165	-155	+10	Tertiary volcanic rocks

[1] From Jennings and others (1977), Lydon and others (1960), and Duffield and Weldin (1976).

Basin Anomalies

After removing regional gravity, the residual anomalies associated with the various basins within the Great Basin range from 15 mgal in Panamint Valley to 50 mgal in Death Valley and Honey Lake Valley (table 6). The calculated thicknesses of sedimentary and volcanic fill within the basins are not only dependent on the size of the gravity anomalies but also on the density contrast between the average density of the fill and that of the enclosing bedrock. Thus, the fill in Death Valley is estimated to be twice as deep as Honey Lake Valley although they both have the same gravity closure (50 mgal), because the density contrast for Death Valley ($\sim$0.45 g/cm^3) is approximately half of that for Honey Lake Valley (0.95 g/cm^3). Similarly, Indian Wells Valley (0.35 g/cm^3) is nearly as deep as Mono Basin (0.8 g/cm^3) although its gravity closure is only about 60 percent that of Mono Basin (table 6).

There is a large uncertainity in most of the density contrasts used to estimate basin depths. The best determined values are those for Indian Wells Valley and Mono Basin, which are based on both seismic control and well data. Formation–density logs, also known as "gamma–gamma," were run by Schlumberger Corporation in two wells in Mono Basin to depths of 1253 m on the south side and 744 m on the north side of Mono Lake. The south–side log indicates a density range of 1.7 to 1.8 g/cm^3 over both the upper 400 m and again in the lower part of the basin over the interval 900–1200 m separated by higher densities (2.0 – 2.3 g/cm^3) between 400 and 900 m (Geothermal Resources International, 1971; Getty Oil Company, 1971). Density contrasts for most of the other basins listed in Table 6 are uncertain by at least $\pm$25 percent.

One of the unresolved problems in the analysis of basin anomalies is that many of the gravity gradients associated with the faulted edges of the basins extend onto bedrock outcrops and cannot be fully explained by any configuration of low–density material underlying the valley (Mabey, 1963; Chapman and others, 1973; Kane and others, 1976).

Relation to Major Faults

Strong gravity gradients occur along most of the major historic and Quaternary faults, and the gradients' points of inflection have been used to locate buried scarps along the Garlock, Sierra Nevada and Death Valley fault zones (Pakiser and others, 1964; Mabey, 1956). Concealed faults were revealed by the steep gravity gradients surrounding Long Valley and Mono Basin (Pakiser, 1961; Pakiser and others, 1960). In Indian Wells and Owens Valleys, the locus of gravity inflection points (and thus the interpreted location for the main Sierra fault) is displaced into the basin about 1 ½ km from the contact between basin sediments and basement rock, suggesting that some exposed scarps have eroded back a considerable distance (Healy and Press, 1964; Pakiser and Kane, 1962). However, detailed gravity analyses in Indian Wells Valley, Owens Valley, Carson Valley, and Surprise Valley indicate that many parts of these fault zones consist of a series of step faults combined with warping as opposed to displacement along a single fault (Healy and Press, 1964, figure 10; Pakiser and Kane, 1962; Tabor and Ellen, 1976; Griscom and Conradi, 1976). The linear gravity high over the Warner Mountains on the west side of the Surprise Valley fault is probably associated with local uplift and westward tilting of a dense core of crystalline rocks draped by the exposed Tertiary volcanic and sedimentary rocks (table 5). Cobbles and boulders of granitic rock near the base of the oldest (Oligocene) sedimentary rocks now exposed in the Warner Mountains (Duffield and Weldin, 1976, p. D8) lends credence to the existence nearby of exposed crystalline rocks at the time of deposition.

Gravity gradients do not occur everywhere along the major faults, and places without gradients are areas where the displacements either are small or juxtapose rocks differing little in density. A number of Quaternary faults within the ranges themselves have no gravity expressions but have significant displacements (Stewart, 1978).

Some of the Surprise Valley frontal faults, along which hot springs are present, have small associated gravity highs of ½ to 1 ½ mgal. The anomalies presumably reflect local hydrothermal alteration and induration of the sediments (Griscom and Conradi, 1976).

Geologic and seismic evidence in Nevada suggests that the normal faults there probably do not penetrate deeply into the continental lithosphere but flatten instead with depth (Eaton and others, 1978). There have not been any gravity studies in eastern California of the configuration of normal faults at depths greater than the base of the sediments, and this avenue of research represents perhaps the greatest remaining challenge in this area.

KLAMATH MOUNTAINS PROVINCE

by Andrew Griscom[1]

The Klamath Mountains have maximum elevations of 2500 to 3000 m and average elevations (figure 4) of 750 to 1350 m. In general the rocks of this province (Irwin, 1977; Hamilton, 1978) are a tectonic assemblage of fragments from Mesozoic and Paleozoic island arcs, melange belts, and ophiolite masses, and are separated from each other by major thrust faults dipping generally to the east. These rocks, particularly the eastern ones, are variably metamorphosed and are intruded by granitic and dioritic plutons, chiefly of Mesozoic age. Beneath the layered Paleozoic rocks of the eastern part of the province is exposed the Trinity assemblage of ultramafic and mafic rocks, considered to be the lower portion of a large ophiolite sequence of early Paleozoic age (Lindsley–Griffin, 1973).

The Bouguer gravity anomalies of the Klamath Mountains slope down to the east from values of about –50 mgal in the northwest corner to a low of –130 mgal near the north border of the state at longitude 123°W. This gradient is mostly the result of two effects: (1) the eastward transition from oceanic to continental crust and mantle and (2) the isostatic effect of the thicker crust eastward as inferred from the increase in average altitude (figure 4). Increased crustal thickness seems an especially likely explanation here because the rock densities at the surface and near the surface (as inferred from local gravity anomalies) are relatively high.

Over the central part of the province, the Bouguer gravity pattern is generally an irregular series of closed highs and lows, many of which are equidimensional and others of which trend north or northwest. The average background gravity level in this central area is about –100 mgal; only local anomalies are markedly above or below this level. The background level is

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Table 6. Estimated thicknesses of fill in the major basins within the Great Basin sector of California.

Basin	*Residual gravity anomaly (mgal)*	*Est. max. thickness of fill (km)*	*Density contrast assumed (g/cm^3)*	*Reference*	*Remarks*
Long Valley	44	3.0	0.45	Kane and others, (1976)	Revised from earlier study of Pakiser (1961) by alloting 10 mgal of anomaly to a deeper source within bedrock.
Mono Basin	47	2.5	0.8	Pakiser (1976), Gilbert and others (1968)	Estimated thickness revised from earlier publication (Pakiser and others, 1964, figure 10) based on new seismic and drilling data.
Death Valley	50	3.0	0.35–0.55	Mabey (1963); Hunt and Mabey (1966, figure 82)	Used variation in density contrast of 0.55 g/cm^3 at surface decreasing to 0.35 below a depth of 1.5 km.
Indian Wells Valley	30	2.6	0.35	Healy and Press (1964); von Huene, (1960)	Depth partially controlled by seismic refraction methods.
Owens Valley	43	2.4	0.5	Kane and Pakiser (1961, figure 5)	Near center of Owens Lake.
Surprise Valley	30	1.5	0.45	Gimlett (1960a); California Department of Water Resources (1965, v. 1, p. 170–171)	Density contrast based on 2.48 g/cm^3 taken for Tertiary volcanic rocks minus 2.03 g/cm^3 for lake sediments based on measurements of drill cores.
Honey Lake Valley	50	1.5	0.95	Gimlett (1960b); California Department of Water Resources (1965, appendix C, p. 193–195)	Contrast based on 2.78 g/cm^3 for 6 samples of metamorphic bedrock minus 1.83 g/cm^3 based on a weighted average of 9 samples of outcropping lacustrine sediments and Miocene and Pliocene ash, clay, and silt.
Saline Valley	40	0.9	0.35	Mabey (1963)	Total residual anomaly not caused by just sedimentary fill.
Panamint Valley	15	0.6	0.35	Mabey (1963)	Young valley with thin deposits.

consistent with an isostatic factor of about 25 mgal/300 m considering that the average altitude is 1050 to 1200 m (figure 4). The relative abundance of gravity highs suggests that the average density of the upper crust in the Klamath Mountains is considerably higher than that of the Coast Ranges, where a gravity minimum of –115 mgals is associated with an average elevation of only 1050 m (figure 4). Correlations of individual anomalies with geology in this central area are only partly clear. The series of central gravity highs with maximum closures of –70 and –75 mgal has no obvious source, although there appears to be a general correlation with higher grade metamorphic rocks of the amphibolite facies (Griscom, 1973a; Kim and Blank, 1973). Perhaps fault slices of dense ophiolitic rocks are present in the subsurface.

Certain batholiths in the western part of the province are associated with gravity highs, probably because the rocks are mafic diorite (Lanphere and others, 1968, p. 1038). Other quartz diorite plutons in the eastern part of the province are associated with gravity lows(closure of –110 mgal, lat 40°40'N, long 122°45'W west of Redding, and closure of –115 mgal at lat 41°20'N, long 123°00'W).

In the northwestern part of the Klamath Mountains is a triangular area above –70 mgal, separated from the rest of the province by a northeast-trending gravity step of about 30 mgal amplitude (Kim and Blank, 1973, p. 6). Within this triangular area, four closed highs with peak amplitudes of –40, –50, and –55 mgal are all associated with masses of ultramafic rocks. The gravity step corresponds with a series of thrust faults, and the high gravity values northwest of the step may indicate thick masses of ultramafic rocks, probably flat-lying fault slices (Kim and Blank, 1973) with associated volcanic rocks, and probably concealed in large part by the overlying sedimentary rocks.

Extending up the east side of the Klamath Mountains province at longitude 122°40' is a row of gravity highs with maximum closures from south to north of –65, –85, –70, and –85 mgal, plus associated highs of –95 and –80 mgal a few kilometers to the east and west respectively. These anomalies are probably all caused by the relatively dense rocks of the Trinity assemblage, a probable ophiolite sequence. The most extensive gravity high, which has a maximum closure of –70 mgal, was discussed by LaFehr (1966), who pointed out the association of the south half of the feature with ultramafic rocks of the Trinity assemblage and calculated that a sheet about 2 km thick with a density contrast of 0.6 g/cm^3 could account for the anomaly. The analysis indicates that the sheet extends in the subsurface north of the exposed Trinity assemblage. I have shown (Griscom, 1977) that the maximum gravity closures within the southern part of the exposed Trinity assemblage are associated with the mafic parts of the ophiolite rather than the ultramafic rocks. Kim and Blank (1973) suggested that the absence of a gravity high over the southern part of the ophiolite between the –85 and –95 mgal closed gravity highs indicates that the sheet must be thin. In 1977 I showed by analysis of aeromagnetic data that here near the –110 mgal closed gravity low the sheet may actually have its maximum thickness, possibly more than 6 km (Griscom, 1977). The serpentinization of the ultramafic rocks has reduced their density to a value similar to that of the country rocks, so there is no gravity anomaly. The Trinity assemblage extends in the subsurface (Griscom, 1973) below the associated magnetic and gravity highs (–60 mgal closure) at Redding (lat 48°35'N, long 122°20'W).

The north end of a seismic-refraction profile (Eaton, 1966) is located at Shasta Lake, 20 km north of Redding. Here the upper crust is composed of material in which longitudinal waves have a velocity of 5.9 km/s (density 2.67 g/cm^3) down to 6 km below sea level, and other material with a velocity of 6.8 km/s (density 2.99 g/cm^3) lies below that depth. The details below 6 km are obscure, but assuming a simple crust, then the base of the crust should be at a depth of about 32 km. The proposed northern extension of the Trinity assemblage beneath the northernmost gravity high (–85 mgal closure at lat 41°50'N) is problematical because the south-dipping basal thrust fault at the base of the assemblage crops out at Yreka (lat 41°45'N) and trends northeast across the gravity saddle in this location. I believe, however, that the northern extension of the gravity feature is too compelling to disregard, and I suggest that there are structural complications, perhaps including repetition of the complex by thrust faults, such that the assemblage extends in the subsurface north of Yreka to underlie the –85 mgal gravity closure. The interpreted extent of the Trinity assemblage from south to north in California is over 170 km and the maximum outcrop width from west to east is more than 50 km. Alternatively, the gravity feature may consist of three different ophiolite masses now tectonically juxtaposed (Hamilton, 1978), with the discontinuities approximately located on the west margin of the assemblage at longitudes 122°15'W and 122°45'W, and with both discontinuities striking northeast.

CASCADE RANGE AND MODOC PLATEAU

by Andrew Griscom[1]

The Cascade Range physiographic province in northern California is dominated by two irregular areas of high topography centered around two major volcanic centers, Lassen Peak (lat 40°30'N, long 121°30'W), and Mount Shasta (lat 41°25'N, long 122°10'W) plus the nearby Medicine Lake Highlands to the east (lat 41°35'N, long 121°35'W). South of Mount Shasta the province is nearly disconnected by an eastward projection of the Klamath Mountains Province, the boundary of which here approximately follows the –115 mgal gravity contour. The Tertiary flows and pyroclastic rocks of the western Cascade Range are exposed only north of Mount Shasta (MacDonald, 1966) and were eroded to rolling hills before renewed volcanism beginning in Pliocene time built the large volcanoes of the High Cascades, predominantly composed of andesite, basalt, and dacite.

East of the Cascade Range Province is the Modoc Plateau, a region of young volcanic landforms separated by broad basalt plains (MacDonald, 1966). The plateau is characterized by block faulting, and the locations of its physiographic boundaries with the Cascade Range to the west and the Great Basin to the east are indefinite. Structural depressions commonly contain Quaternary lake beds. The total thickness of the Tertiary and younger volcanic rocks is unknown but is at least several kilometers. The age and lithology of the underlying older rocks are also unknown.

A regional Bouguer gravity gradient between about –110 to –140 mgal slopes down from west to east across the Cascade Range (LaFehr, 1965) and may reflect either thickening of the entire crust to the east or thickening to the east of the low–

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density upper part while the total crustal thickness remains constant (LaFehr, 1965; Griscom, 1973). The isostatic effects in either case will cause the observed increase in average altitude to the east (figure 4). Simila (1978) reported an average crustal thickness for the Cascade Range of 35 km from seismic–refraction data.

LaFehr (1965) removed the regional gravity field from a Bouguer gravity map of the Cascade Range in California and demonstrated two similar subcircular residual gravity minima with amplitudes about –50 mgal and diameters of about 50 to 70 km, associated with the Lassen and the Shasta–Medicine Lake volcanic areas. These lows are obvious on the State gravity map. Earlier, Pakiser (1964) showed that the Lassen gravity low could be accounted for by a near–surface slab of low–density rocks with its bottom about 8 km below sea level, if the density contrast were –0.2 g/cm^3. Pakiser believed that low–density deposits of volcanic origin in a large subcircular volcano–tectonic depression were the most likely source of the gravity anomaly, although a batholith was another possibility, and that the mass excess of the Cascade Range was in approximate isostatic equilibrium with the buried low–density mass. LaFehr (1965) came to similar conclusions for the Shasta–Medicine Lake gravity low, pointing out that the association of the two minima with major volcanoes was strong support for an igneous source. He deduced that the mass of Mount Shasta was itself compensatesd by a residual gravity low of about –35 mgal in the immediate vicinity of the mountain.

Kim and Blank (1973) showed that the west side of the Shasta gravity low was composed of two steep gradients separated by a flatter bench 10–20 km wide. The western gradient marked the contact between the Klamath Mountains Province and the Tertiary volcanic rocks of the western Cascade Range and was probably the expression of concealed high–angle marginal faults. The eastern gravity gradient was considered to correspond in turn with the western limit of younger (Pliocene and Pleistocene) volcanic rocks of the High Cascades associated with the circular Shasta gravity low. My calculations on aeromagnetic data over the western gravity gradient northwest of Mount Shasta (Griscom, 1977) showed that the top of the Trinity assemblage may be offset steeply downward to the east and may there extend beneath the west side of the Shasta gravity depression, thus offering independent support for the interpreted faults.

Chapman and Bishop (1968a) noted the gravity high (maximum contour –140 mgal) associated with the Medicine Lake Highland on the east border of the Shasta gravity minimum and stated that the anomaly may be caused either by the volcanic rocks of this large shield volcano with central collapse caldera (Anderson, 1941) or by an underlying intrusive mass. They favored the latter explanation because most Cascade Range volcanoes show associated gravity minima.

Calculations by LaFehr (1965) showed that the steep gravity gradients on the west sides of the two major gravity minima indicate steep west contacts for the underlying low–density rocks. These steep contacts may be a series of normal faults bordering the two volcano–tectonic depressions. However, LaFehr did not take into account the fact that the westernmost part of his residual anomaly for the Shasta feature is associated with older Tertiary volcanic rocks rather than the younger ones of Mount Shasta, and thus his Shasta anomaly is not fully isolated. Some of his inferred border faults must border the Cascade Range province itself rather than the inferred Shasta volcano tectonic depression.

Interpretation of the gravity minima depends strongly upon the assumed density contrast between the younger low–density mass and the older basement rocks. LaFehr (1965) assumed that the basement rocks beneath Mount Shasta were similar to those exposed near the bottom of the mountain on the north (a small steptoe), south, and southeast sides. His density measurements on representative rock samples from this area gave results of 2.72 ± 0.18 g/cm^3 (50 samples) for the "Paleozoic basement" and 2.52 ± .13 g/cm^3 for Tertiary volcanic rocks (58 samples). These data suggest that the density contrast of –0.2 g/cm^3 used in the calculations is reasonable, but the density of pyroclastic rock units is difficult to measure accurately. Furthermore, if the Trinity assemblage lies beneath Mount Shasta, the density contrast may be larger. The nature of the basement rocks beneath Lassen Peak is unknown, but the similarity of its gravity expression with that of Shasta suggests basement of similar density. I believe that low–density volcanic deposits may not be a sufficient explanation for these features because the calculated models of LaFehr (1965) and Pakiser (1964) are slabs with relatively constant thickness and steep margins. Such configurations suggest on tectonic grounds the presence of concealed plutons of similar or larger diameter beneath the gravity minima. The calculated models (LaFehr, 1965) also show roots with diameters of about 15 km centered under the volcanoes and extending down about 10 km. These roots may represent great thicknesses of volcanic rocks but more probably represent the stocks that fed the eruptions. The arcuate topographic scarp cutting the Klamath Mountains around the south and west side of the Shasta gravity low was interpreted by Heiken (1976) as evidence for a tectonic depression formed by collapse over a batholith. North of Lassen Peak a small gravity low with a minimum contour of –155 mgal (lat 40°40′N, long 121°30′W) is associated with several major andesitic pyroclastic cones having local heights of 800 to 1100 m. This anomaly may be caused by a small near–surface stock 10–20 km in diameter, and the local topography suggests a caldera.

The various tectonic assemblages of the Klamath Mountains disappear to the southeast beneath the younger cover of the Great Valley and Cascade Range, reappearing in the western part of the northern Sierra Nevada (Davis, 1969). The continuity of these assemblages, where concealed, is a matter of some interest. I have interpreted from gravity and magnetic data a major concealed northeast–trending fault, possibly of Cretaceous age, passing across the north end of the Great Valley (Griscom, 1973). If extended to the northeast, this fault lies about 20 km south of Lassen. I have also interpreted aeromagnetic data (Isidore Zietz, unpublished map) over the southern Cascades and northern Sierra Nevada to indicate that Sierra northwest structural trends can be traced into the Cascade Range Province at least as far as a point about 25 km south of Lassen Peak. Blake and Jones (1977) suggested that a rift zone may have extended northeast from the vicinity of Red Bluff (lat 40°10′N, long 122°15′W), presumably near the aforementioned fault, resulting in northwest movement of the Klamath block relative to the Sierra block. Hamilton (1978, figure 4 and p. 60), in an extension of ideas developed by Hamilton and Myers (1966), suggested that the Klamath Mountains were rifted and rotated away from the Sierra Nevada leaving a gap about 50–75 km wide in the area of the southern Cascades, the gap having been filled with Cenozoic volcanic rocks and sediments. The shortest distance between outcrops of Klamath and Sierra basement is about 62 km (Lydon and others, 1960). The suggested location for the rift zone is supported by the rather rectangular

outline of the Lassen gravity low, the southeast edge of the proposed rift being located approximately on the −160 mgal contour at the southeast side of the low, and the northwest edge of the rift on the −145 mgal contour at the northwest side of the low. The steep regional gravity gradient extending from the Sierra Nevada northwest across the proposed rift zone does not necessarily contradict the existence of the rift because this gradient is isostatic in origin and related to the topography (figure 4), which probably postdates the rifting. The close relation between regional gravity and regional topography in California implies that the regional gravity field has the same age as the topography, predominantly late Cenozoic.

The Lassen and Shasta gravity lows are separated by a northeast-trending gravity ridge with maximum contours of −105 and −125 mgal. This gravity ridge, described below, extends farther northeast across the entire Modoc Plateau as a series of gravity highs, and the composite gravity ridge suggests some fundamental tectonic division of the Cascade Range and Modoc Plateau into separate halves in California. The southeast side of this ridge may be the northwest side of the proposed rift zone described above. The gravity ridge probably represents a structural high of the basement underlying the Cenozoic volcanic rocks. The volcanic rocks are presumed to have a lower density than the basement rocks.

The gravity data do not always indicate agreement with the defined physiographic boundaries between the Cascade Range Province and the Modoc Plateau. The east side of the Lassen gravity low corresponds with the local boundary between the physiographic provinces, but the north half of the Shasta–Medicine Lake low lies in the Modoc Plateau, including the topographically low area of Butte Valley and Meiss Lake. Evidently in this regon the boundary of the geophysical data transgresses the physiographic boundary.

The regional gravity field over the Modoc Plateau ranges from about −140 mgal at the west side to about −175 mgal on the east side. Just as in the Cascade Range, this gradient may be caused either by thickening of the entire crust to the east or by a thickening to the east of the low-density upper part while holding the total crustal thickness constant (LaFehr, 1965; Griscom, 1973). A third alternative may be the best explanation for the regional gravity field. Because of the structural similarities and indefinite boundaries between the Modoc Plateau and the Great Basin, the Modoc Plateau may have the same thinned crust (Hamilton, 1978) and anomalous low-density mantle as is present in the Great Basin (Pakiser, 1963; Pakiser and Steinhart, 1964; Prodehl, 1970). The presence of low-density upper mantle can explain the otherwise unusual association of thinned crust, low gravity, and moderate elevation. Thus the eastward decrease in gravity (in the Cascade Range as well as the Modoc Plateau) may represent a transition from more normal crust and mantle to anomalous crust and mantle, directly related to the extensional tectonics of the Great Basin Province.

A line of closed gravity highs trends northeast across the Modoc Plateau from the northeast-trending gravity ridge separating the two gravity depressions of the Cascade Range. The row of highs was described by Chapman and Bishop (1968a), who suggested as possible sources near-surface basement rocks, intrusive rocks underlying the volcanic rocks, and lateral density changes within the volcanic rocks. The on-trend gravity ridge of the Cascade Range reflects shallow basement between the structural depressions of Mount Lassen and Shasta–Medicine Lake, and the row of gravity highs across the Modoc Plateau probably has a similar source. The Modoc anomalies have maximum amplitudes of about 20 mgal, so that if the density contrast between the volcanic rocks and the basement rocks is 0.2 g/cm^3 (LaFehr, 1965, p. 5584), then the relative elevation of the basement at the highs is approximately 2.4 km. Approximately 25 km north of the prominent high (long 121°W) with a closed contour of −130 mgal is a gravity low with a closed contour of −165 mgal. More detailed gravity data in the vicinity of this gravity low (Chapman and others, 1978) reveal a large sub-circular fault-bounded basin or possible caldera filled with low-density sedimentary or volcanic rocks.

Chapman and Bishop (1968a) described various local gravity lows caused by Quaternary lake sediments filling structural depressions in the volcanic rocks. All major lakes and dry lakes have associated gravity lows of this sort, ranging in amplitude from −10 to −20 mgal. Density contrasts between sediments and volcanic rocks are probably at least 0.5 g/cm^3, so that the maximum thicknesses of sediments may be no greater than about 1 km unless concealed sediments of higher density underlie them. These gravity lows are found at the following locations, from southeast to northwest (lat 40°30′ to 42°N): Eagle Lake, Madeline Plains, Big Valley, Big Lake, Goose Lake, Clear Lake Reservoir, Tule Lake Sump, and Lower Klamath Lake. Many of the lows are bordered by local steep gravity gradients trending northwest or, less commonly, north. The gradients probably represent faults or steep downwarps related to similar structural trends in the Great Basin Province to the east and southeast.

The Likely fault is the major known Quaternary fault within the Modoc Plateau. The fault has little if any influence on the gravity field (Chapman and Bishop, 1968a).

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APPENDIX

Gravity Measurements, Reductions, and Conversion Formulas to IGSN 71 and GRS 67

by

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Base Stations, Gravity Meters, and Calibration

The prime gravity base station to which all the measurements of gravity differences at land stations in California have been referenced is Woollard's main control station WA 86 at San Francisco Airport (Behrendt and Woollard, 1961, table 2; Woollard and Rose, 1963, p. 94). Using Behrendt's (written communication, 1963) value at WA 86 of 979988.33 mgal, Chapman (1966) established 360 base stations in California with LaCoste and Romberg gravity meter G22. A correction factor of 1.0009 was applied to the factory calibration based on recommendations by the manufacturer at that time and on tests along the Yosemite Calibration Loop (Barnes and others, 1969). Most of the gravity data in southern California and northwestern California are tied to these bases, and their observed gravity values have been determined relative to the published base station values given by Chapman (1966, Supplement 1).

In northern California, additional work was done in 1968–1970 to strengthen the existing base network, and 28 new base stations were added in the Central Valley, Sierra Nevada, and northern Coast Ranges. The new data for the four prime bases in these areas are listed in Table 7, and the new base network is shown in Figure 8. Station A at the U.S. Geological Survey office in Menlo Park (Chapman, 1966, p. 36, station 173) was used as the reference base for the new work, station WA 86 at San Francisco Airport having been made unoccupiable by new airport construction in 1966. Five ties were made between Menlo Park and San Francisco Airport before the 1966 construction which yielded the gravity difference of 29.59 ± .01 mgal (s.e.). The prime bases at Porterville and Sonora are particularly well established relative to Menlo Park, so that possible relative vertical movements between the coast of California and the Sierra Nevada greater than 5 cm should be detectable by repeating measurements of gravity differences between these base stations.

The 28 new base stations in northern California (figure 8) and most of the gravity data in northern California were obtained using calibrations of LaCoste and Romberg gravity meters that are 3 parts in 10,000 lower than the calibration standard used to establish the California base station network (Chapman, 1966). The calibration standard was primarily the Yosemite Calibration Loop for which a correction factor of 1.0009 had been determined for LaCoste and Romberg meter G22 to bring its data in line with meter G17, which had been calibrated on the North American Calibration Range from Costa Rica to Point Barrow, Alaska (Chapman, 1966, figure 1). However, more comparisons were made in 1968 between G22 and G17 as well as Defense Mapping Agency meter G115 (factor 1.00012). The results suggested that the correction factor for G22 should be reduced from 1.0009 to 1.0006. This change was verified in 1971 by a direct comparison of gravity differences of base station values in east–

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Table 7. Observed gravity values, number of ties to Menlo Park, and gravity meters used for establishing the four prime base stations in east–central California. [Locations of the base stations are shown in Figure 8 by both name and number. Prime bases are those which have 14 or more ties to station A in Menlo Park and standard errors of ±.01 mgal or less.]

Station Number	Place names	Observed gravity (mgal)	Standard deviation (mgal)	Standard error (mgal)	Ties (one way) to Menlo Park	Gravity meters used in decreasing number of ties
A2	Fresno[1]	979,832.95	.025	±.006	20	G17,G115,G8,G58, G65,G129,G143,G22
A7A	Porterville[1]	979,746.33	.028	±.005	28	G17,G8,G58,G67
CH122	Auburn[2]	979,953.28	.038	±.009	18	G17,G8,G58,G65, G67,G22,G143
CH186	Sonora[2]	979,832.11	.025	±.007	14	G17,G8,G58,G67, G22,G143

[1] See Robbins and others (1975a, p. 28, 30) for descriptions and pictures of these bases.
[2] The original descriptions of these stations (Chapman, 1966, p. 31, 37) have been updated and photographs have been taken (Robbins and others, 1976a, p. 20; Robbins and others, 1974, p. 19).

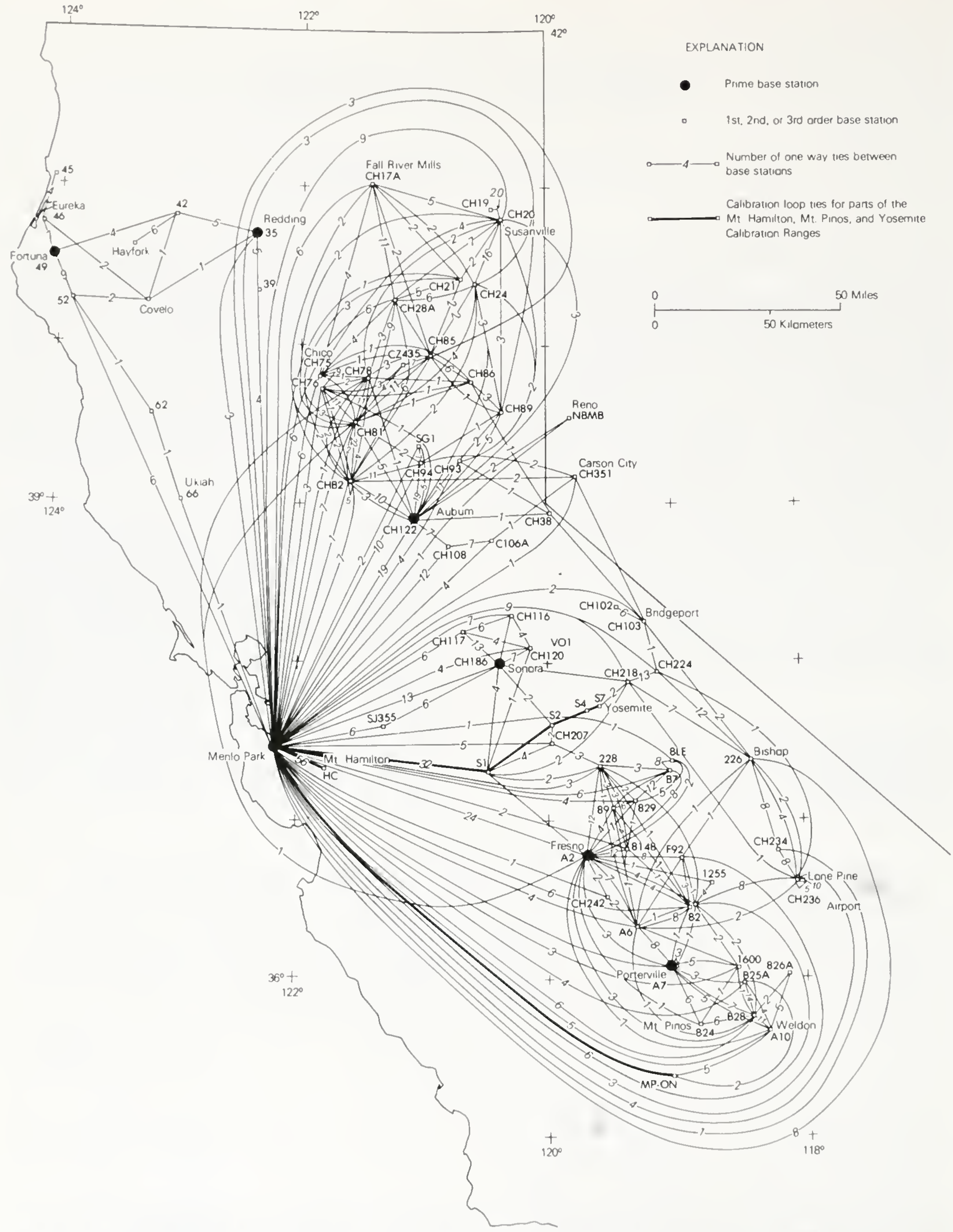

Figure 8. New gravity base station network in east–central California. Observed gravity values for the prime base stations are listed in Table 7. Values for the descriptions of lower–order bases are provided in the local NTIS reports shown in Figure 2.

central California obtained with G17 (figure 9). The revised observed gravity values of the base stations plotted in Figure 9 as well as the pictures, descriptions, and gravity values of the 28 new base stations are presented in the NTIS publications listed by area in Figure 2. Revised values of other base stations in the state as reported by Chapman (1966) can be obtained from the following formula:

$$G_i = 0.9997\ (G_j - 979988.33) + 979988.33 \qquad (1)$$

or more simply

$$G_i = 0.9997\ G_j + 294.00$$

where G_i = Revised observed gravity value in mgal for a given base station whose published value is G_j in mgal (Chapman, 1966). For example, G_j at base station number 103 at Bridgeport is 979395.61 mgal (Chapman, 1966, Supplement). The calculated revised value is 979395.80 mgal or 0.19 mgal higher (see plot of "CH 103", figure 9). The correction ranges from −0.09 mgal at Crescent City to +0.20 mgal at Desconso Valley in the mountains east of San Diego (Base station numbers 1 and 341, Chapman, 1966, p. 36 and 34, respectively). Thus, the calibration problem is not serious, but these corrections should be made to gravity data referenced to 1966 base station values for which the desired accuracy relative to other parts of California is 0.1 mgal or better. A considerable effort was made to hold this accuracy throughout California. Table 8 shows the 17 LaCoste and Romberg meters that were used in obtaining about 30,000 new stations during 1968 to 1971 and their correction factors as determined over the various calibration loops in California (Barnes and others, 1969).

The base stations used by the U.S. Naval Hydrographic Office as references for offshore data were also established with LaCoste and Romberg meters relative to 980118.8 mgal at the National Reference Base in Washington, D.C. (Cliff Gray, personal communication, 1978). The bottom meter data off northern California referred to above were tied to bases at Humboldt Bay Pier B in Eureka and at the foot of Pier 14, Treasure Island, using base values of 980223.36 mgal and 979991.86 mgal, respectively (N.A. Prahl and G.B. Mills, written communication, 1971). Descriptions and observed gravity values at other bases

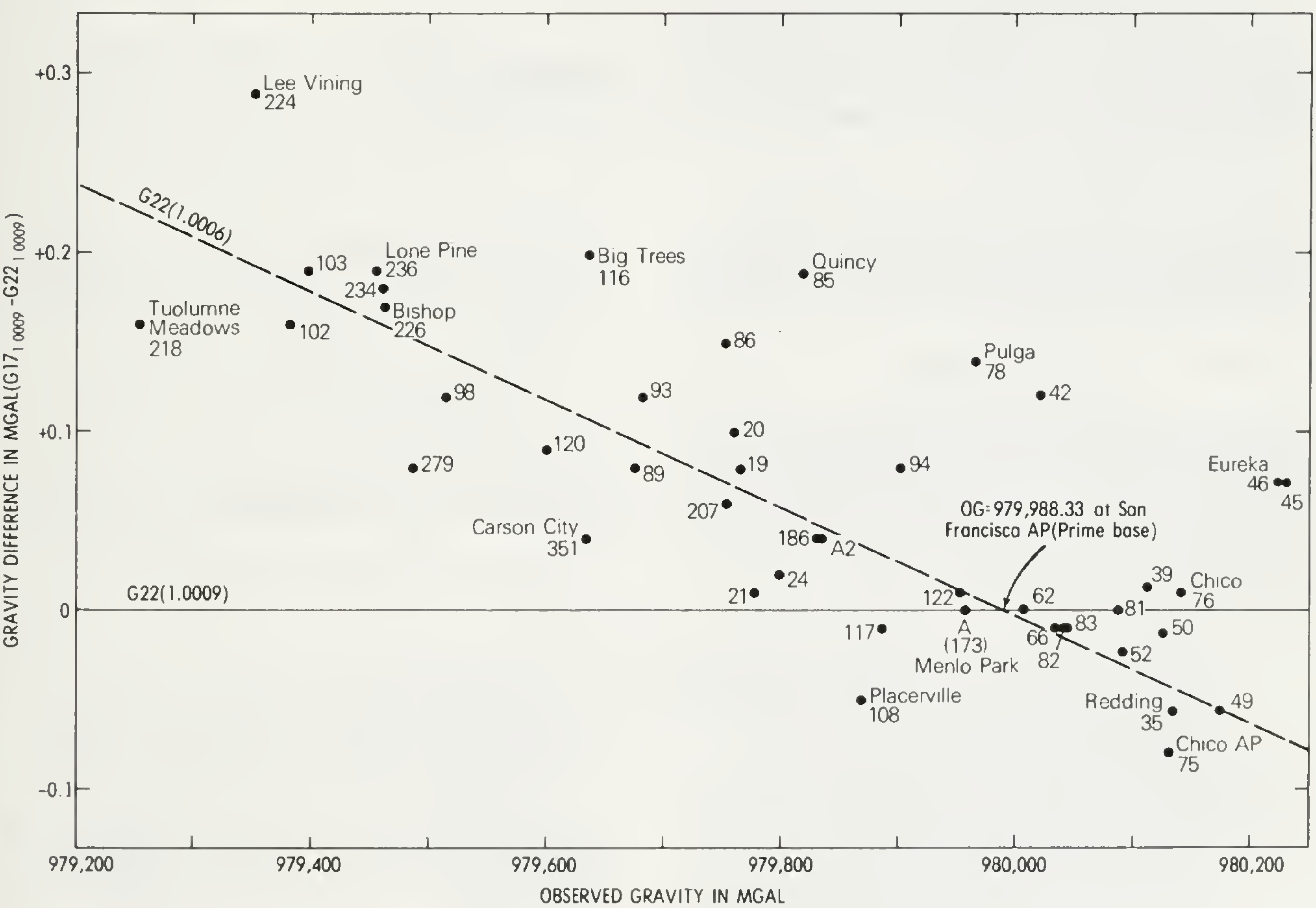

Figure 9. Gravity differences between measurements made at 33 base stations in California with LaCoste and Romberg gravity meter G17 using a correction factor of 1.0009 during 1968–1970 and those made with meter G22 using the same factor (Chapman, 1966). The gravity differences are plotted as a function of observed gravity values and tend to decrease with increasing gravity. This general dependence is removed by reducing the correction factor of meter G22 to 1.0006 (dashed line). The average scatter for G17 (1.0009) − G22 (1.0006) is about ±0.03 mgal, and this variance is a measure of the repeatability of the gravity measurements.

Table 8. Correction factors to factory calibration tables of LaCoste–Romberg gravity meters used in the California gravity program. The following calibration loops are used to determine the factors (see Barnes and others, 1969):

LaCoste–Romberg meter and owner	*Correction factor relative to 1.00016 for G115B*	*Range or loop and number of runs*
G8 U.S. Geological Survey	1.0006[1]	N2, H8, P8, Y5
G10 Defense Mapping Agency	.9997	H2
G12 Defense Mapping Agency	1.0001	H2, C4
G17 U.S. Geological Survey	1.0009	H7, H22, P5, Y9, S3, L3, C3'
G22 Univ. Calif. Riverside	1.0006	Y1, H1
G58 Defense Mapping Agency	.9998	H1, P3
G62 Defense Mapping Agency	1.0004	H4, Y3
G65 Defense Mapping Agency	1.0003	H5, Y2
G102 Stanford Univ.	1.0003	H3, Y2
G115 Defense Mapping Agency	(1.00016)	E1, H5, P4, Y4, S3, L3, C2
G129 Calif. Div. Mines Geology	1.0003	H6, P1
G130 Defense Mapping Agency	1.0003	H4, A1
G143 Defense Mapping Agency	1.0003	H6, P1
G159 U.S. Geological Survey	1.0004[2]	L1, M2
G161 U.S. Geological Survey	1.0002[3]	H6, P1
G172 U.S. Geological Survey	1.0002	H3
G198 U.S. Bur. Mines	1.0005	H3

W = North American Western Calibration Range (Costa Rico to Point Barrow, Ak.)
E = North American Eastern Calibration Range (Key West, Fla. to Washington, D.C.)
H = Mt. Hamilton, Ca.
P = Mt. Pinos, Ca.
Y = Yosemite, Ca.
S = Palm Springs, Ca.
L = Mt. Lassen, Ca.
C = Crater Lake, Ore.
LM = Lookout Mountain, Colo.
M = Mt. Evans, Colo.
A = Anchorage, Ak.

1 This is the factor determined in 1968 to 1971 during its use in California. The main spring in G8 has since been replaced and the meter converted to electronic readout for measuring microgravity changes.

2 Relative to LaCoste–Romberg meter G–1A calibrated on the North American Range (Behrendt, 1962, p. 889). As of 1978, more data on the Mt. Evans loop indicate that the "best" correction factor is 1.0002 for G159 (D.L. Peterson, written communication, 1978)

3 The scatter in the 7 runs with this meter during 1967-1973 was 1.0001 to 1.0005. In 1976, the meter was converted to electronic readout, and this process apparently caused a decrease in the factory calibration by 4 parts in 10,000 based on factory tests in Cloudcroft, New Mexico.

used along the California coast by the Hydrographic Office have not been published, but specific base information can be obtained from their National Standards and Testing Laboratory Branch in Bay St. Louis, Mississippi 39522.

Reduction of Data

All the gravity measurements on land have been reduced to Bouguer anomalies using first a computer program that transforms meter readings in scale divisions to simple Bouguer anomalies (Oliver, 1973, appendix 2) and a second program that makes terrain and curvature corrections and adds them to the simple Bouguer anomalies (Plouff, 1977). The basic procedures and formulas of the reduction are as follows:

(1) The meter readings in scale divisions of both the base and field stations are converted to milligals using stored factory calibration tables and the correction factor for the particular gravity meter (table 8). The meter readings in milligals are then corrected for tidal variations using L.B. Slichter's (written communication, 1969) program and an elasticity factor for earth tides of 1.16. The residual drift is generally removed linearly, although if it is in excess of 0.1 mgal for any given traverse the data are studied for possible tares and non-linear drift is removed. If the residual drift is greater than 0.2 mgal, the data are usually discarded. The gravity difference (Δ g) in milligals is then obtained by taking the difference between the corrected base and corrected field station.

(2) Observed gravity (g_o) = Previously determined Gravity Base Value + Δg.

(3) Theoretical gravity $g_t = 978049\ (1 + 5.229 \times 10^{-3} \sin^2\theta - 5.9 \times 10^{-6} \sin^2\theta)$, where θ = latitude.

(4) Free–air anomaly (FAA) $= g_o - g_t + (9.411549 \times 10^{-2} - 1.37789 \times 10^{-4} \sin^2\theta)\ E - 6.7 \times 10^{-9}\ E^2$, where E is the elevation in feet.

(5) Simple Bouguer anomaly (BA) $=$ FAA$-(1.2774 \times 10^{-2}\ \rho E)$ where ρ = reduction density in g/cm^3.

(6) Curvature correction (CC) $= 4.462 \times 10^{-4} E - 3.28 \times 10^{-8}\ E^2 \times 1.27 \times 10^{-15}\ E^3$ where E is the elevation in feet.

(7) Complete Bouguer anomaly (CBA) = BA – CC + TC where TC = terrain correction for ρ. The terrain correction is generally made manually to a distance of 2.29 km and extended to 166.7 km using the digital model of California and adjacent regions (Robbins and others, 1973).

The offshore data obtained with surface shipboard measurements were reduced to free–air anomalies using the simpler formula:

$$FAA = g_o - g_t + 9.406 \times 10^{-2}\ E$$

where E is the elevation of the gravity meter above the sea surface in feet. Reduction of the ocean–bottom meter data is

Table 9. Comparison between IGSN 71 (Morelli, 1974) and Chapman's (1966) observed gravity values in California and Nevada.

Name and location	Station numbers			Observed gravities		Gravity difference
	IGSN[3]	DMA[3]	Chapman	IGSN (mgal)	Chapman (mgal)	(IGSN–Chapman) (mgal)
San Diego–Lindbergh Field	12027–J	187–0	343	979522.32	979537.05	–14.73
Los Angeles–UCLA	12038–B	420–3	311	979583.10	979597.68	–14.58
Reno–Airport Weather	12099–K	454–2	349	979675.88	979690.39	–14.51
San Francisco–Airport (upper AF disk)	12172–0	133–0	1	979972.37	979986.81[1]	–14.44
Potsdam, Germany	A			981260.19	981274.20[2]	–14.0[2]

[1] California Base Net value determined by H. W. Oliver (in 1970) relative to Chapman's stations 156, 159, 164, 165, and 173.
[2] See Morelli (1974, p. 18) and Woollard (1963, p. 33).
[3] These are the station designations as given by Morelli (1974, p. 48-49) for IGSN and Hauer (1974) for DMA.

based on the following equation (afer Prahl and Mills, written communication, 1971):

$$FAA = g_o - [g_t + F_1 (D-T) - F_2 (2D-T)]$$

where

g_o = observed gravity on the ocean floor
g_t = theoretical gravity at the surface (see above formula)
F_1 = free–air gradient taken to be 9.406×10^{-2} mgal/ft.
F_2 = water slab coefficient of 1.315×10^{-2} mgal/ft.
D = water depth in feet
T = Height of tide above datum in feet.

The equation consists of a free–air and a double Bouguer slab correction for the depth of water and a single Bouguer slab correction for the tide. Inserting the constants and simplifying, the above equation reduces to

$$FAA = g_o - g_t + 0.06776\ D - 0.08091\ T$$

Conversion to IGSN 71 and GRS 67

As most of the onshore and offshore gravity data in California were obtained during 1966–1971, it was reasonable to use the Woollard and Rose (1963) gravity datum and reduce the data on the basis of the 1930 International Gravity formula (Swick, 1942, p. 61). Since the adoption of the new absolute gravity standard "IGSN 71" (Morelli, 1974) discussed above and the "Geodetic Reference System 1967" (GRS 67) (International Association of Geodesy, 1971), new gravity data in California are being processed using these combined systems (see for example Isherwood and Plouff, 1978). Also, some other State gravity maps such as Alaska's (Barnes, 1977) are being compiled with these updated systems. Therefore, it is of interest to set forth what would be involved in making these changes to the approximately 80,000 stations in California and estimating the effect on onshore Bouguer anomalies and offshore free–air anomalies.

Table 9 lists observed gravity values on IGSN 71 and Chapman datums at three stations in California, at one in Nevada, and at Potsdam. The differences (last column table 9) are a function of observed gravity (g_o) and are approximated by the linear relation

$$\Delta g_o \text{ (IGSN 71–Chapman)} = -14.4 + A\ (g_o \text{ Chapman} - 980000) \quad (1)$$

where g_o (IGSN) and g_o (Chapman) are in milligals and A is the change in gravity scale, which appears to average about 4×10^{-4} for successive differences in gravity south of San Francisco (table 10).

Locations	Difference in observed gravity[1] (mgal)	Difference[2] in IGSN–Chapman (mgal)	Apparent[3] change in scale value
Woollard and Rose			
Potsdam - San Francisco	+1287.2	+0.44	$+3.4 \times 10^{-4}$
Potsdam - Reno	+1588.1	+0.51	$+3.2 \times 10^{-4}$
Potsdam - San Diego	+1736.9	+0.73	$+4.2 \times 10^{-4}$
Chapman			
San Francisco - San Diego	+450.05	+0.29	$+6.4 \times 10^{-4}$
San Francisco - Los Angeles	+389.13	+0.14	$+3.6 \times 10^{-4}$
San Francisco - Reno	+296.42	+0.07	$+2.4 \times 10^{-4}$

Table 10. Changes in the scale values for IGSN 71 relative to that for Woollard and Rose (1963) and Chapman (1966).

[1] Based on IGSN 71 values.
[2] From table 9.
[3] For example: $+.44/+1287.2 = +3.4 \times 10^{-4}$

The effect of converting from the 1930 to the 1967 reference ellipsoids is

$$\Delta g_t \ (1967\text{–}1930) = -17.2 + 13.6 \sin^2\theta \qquad (2)$$

where θ is the latitude and Δg_t is in milligals (International Association of Geodesy, 1971, p. 60).

Thus, the effect on free-air and Bouguer gravity anomalies (Δg_a) of adopting IGSN 71 and GRS 67 is

$$\Delta g_a = \Delta g_o - \Delta g_t$$
$$\Delta g_a = 2.8 - 13.6 \sin^2\theta + 4 \times 10^{-4} (g_o - 980000)$$

where g_o and Δg_a are in milligals.

For values of θ and g_o in California, Δg_a varies from about -1.5 mgal at San Diego to about -3.2 mgal near the Oregon border and is about -2 mgal in central California (table 11).

Location	*Latitude*	*Change in theoretical gravity (mgal)*	*Change in observed gravity (mgal)*	*Bouguer anomaly (mgal)*
San Diego	32°44′	−13.2	−14.7	−1.5
Los Angeles	33°57′	−13.0	−14.6	−1.6
San Francisco	37°37′	−12.1	−14.4	−2.3
Reno, Nev.	39°31′	−11.7	−14.5	−2.8
Medford, Ore.	42.22′	−11.1	(−14.4)[1]	−3.3

[1] Based on a comparison of observed gravity values at stations at Medford Airport which are not exactly at the same location but very close. This difference may be 0.1 too large, in which case the resulting change in Bouguer anomaly at Medford would be −3.2 mgal.

Table 11. Changes in Bouguer anomalies resulting from adoption of GRS 1967 and IGSN 71.

81713–650 12–80 OSP 1250 LDA

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